**EXHIBIT PC-1**

Exhibit PC-1

UNIVERSITY OF MARYLAND

Professor Peter Cramton

Contact Information
Redacted

22 May 2023

**Peter Cramton** is Professor of Economics Emeritus at the University of Maryland. Since 1983, he has conducted research on auctions and market design, with a focus on the design of complex markets to best achieve goals. Applications include electricity markets, financial markets, and auctions for radio spectrum. He has introduced innovative market designs in many industries. Cramton has advised numerous governments on market design and dozens of bidders in major auctions. He is chief economist and advisor for startups in finance, insurance, and communications. From 2015-2021, he was an independent director of the board of the Electric Reliability Council of Texas (ERCOT). He received his B.S. in Engineering from Cornell University and his Ph.D. in Business from Stanford University.

## Academic Positions

*Professor of Economics*—Department of Economics, University of Maryland, August 1996 to present, Emeritus since July 2018.

*Professor of Economics*—Department of Economics, University of Cologne, January 2018 to December 2022.

*Research Affiliate*—Reinhard Selten Institute, January 2017 to present.

*International Faculty*—Department of Economics, University of Cologne, July 2015 to December 2017.

*Part-time Professor of Economics*—Department of Economics, European University Institute, September 2015 to August 2017.

*Associate Professor of Economics*—Department of Economics, University of Maryland, August 1993 to June 1996.

*National Fellow*—Hoover Institution, Stanford University, September 1992 to August 1993.

*Associate Professor of Economics and Management*—Yale School of Management, Yale University, July 1988 to August 1993.

*Assistant Professor of Decision Theory*—Yale School of Management, Yale University, July 1984 to June 1988.

## Education

*Stanford University*, Doctor of Philosophy, June 1984, Graduate School of Business.
Dissertation: *The Role of Time and Information in Bargaining*.

*Cornell University*, Bachelor of Science with distinction, May 1980, School of Operations Research and Industrial Engineering. Graduated first in class.

### Recent Courses

Auctions and Market Design. Master/Doctoral course on auctions and market design.

Economic Engineering. Master/Doctoral introductory course on auctions, matching, and behavioral economics applied to market design.

*Advanced Microeconomics*. Doctoral course in game theory with emphasis on auctions and market design.

*Methods and Tools of Economic Analysis*. Undergraduate introduction to the mathematical tools used in economics.

*Game Theory*. Undergraduate introduction to modern game theory.

*Market Design*. An advanced undergraduate course on auction and market design.

### Research Interests

Market design, auction theory and practice, bargaining theory, industrial organization, experimental economics, contract theory, game theory, decision theory, labor economics, information economics, and law and economics.

### Honors

Fellow of the Econometric Society, 2021.

Winner of the Utah Winter Finance Conference Best Paper Award, 2015.

Winner of the AQR Insight Award for most insightful unpublished paper in finance, 2014.

Distinguished Service Award, American Association for Homecare, 2012.

Resident Scholar, Rockefeller Foundation, Villa Serbelloni, Bellagio, Italy, Spring 2007.

Departmental Undergraduate Teaching Award, Spring 1996 (2), Spring 1997 and Spring 2002.

Departmental Graduate Teaching Award, Fall 1994, Fall 1998, and Fall 2007.

Hoover National Fellow, Hoover Institution, Stanford University, 1992-93.

Winner of the *1984 Leonard J. Savage Thesis Award* for an outstanding dissertation in Bayesian Economics.

American Assembly of Collegiate Schools of Business Doctoral Fellowship, 1983-84.

National Association of Purchasing Management Scholarship, 1983-84.

Dean's Award for Service to Stanford University, 1983-84.

Two-time recipient of *Stanford Merit Fellowship*, 1981-83.

Elected by the Operations Research faculty as outstanding senior, 1980.

### Affiliations

Econometric Society, American Economic Association, Society for Economic Analysis, and Society for the Promotion of Economic Theory.

### Research on Auction and Market Design

### Highlights

*Global Carbon Pricing—The Path to Climate Cooperation* (with David JC MacKay, Axel Ockenfels and Steven Stoft), *MIT Press*, 2017.

"The High-Frequency Trading Arms Race: Frequent Batch Auctions as a Market Design Response," (with Eric Budish and John Shim), *Quarterly Journal of Economics*, 130:4, 1547–1621, November 2015.

"Demand Reduction and Inefficiency in Multi-Unit Auctions," (with Lawrence M. Ausubel, Marek Pycia, Marzena Rostek, and Marek Weretka), *Review of Economic Studies*, 81:4, 1366-1400, 2014.

*Combinatorial Auctions*, (with Yoav Shoham and Richard Steinberg) MIT Press, 2006.

"Strikes and Holdouts in Wage Bargaining: Theory and Data," (with Joseph S. Tracy) *American Economic Review*, 82, 100–121, 1992. Reprinted in Bengt Holmstrom, Paul Milgrom, and Alvin E. Roth (eds.), *Game Theory in the Tradition of Bob Wilson*, Berkeley Electronic Press, May 2002.

"Strategic Delay in Bargaining with Two-Sided Uncertainty," *Review of Economic Studies*, 59, 205–225, 1992.

"Dissolving a Partnership Efficiently," (with Robert Gibbons and Paul Klemperer) *Econometrica*, 55, 615–632, 1987. Reprinted in Paul Klemperer (ed.), *The Economic Theory of Auctions*, Volume 2, Cheltenham, UK: Edward Elgar, 2000.

---

**Market design**

"Market Design, Human Behavior and Management," (with Yan Chen, John A. List, and Axel Ockenfels) *Management Science*, 67, 5317-5348, 2021.

"Improving the Cost-Effectiveness of the Conservation Reserve Program: A Laboratory Study," (with Daniel Hellerstein, Nathaniel Higgins, Richard Iovanna, Kristian López-Vargas, Steven Wallander) *Journal of Environmental Economics and Management*, 108, 2021.

"It is Time to Auction Slots at Congested Airports," (with Martin Bichler, Peter Gritzmann, and Axel Ockenfels) *Vox-CEPR Policy Portal*, 10 January 2021.

"How Softening an Auction Reserve Price Not Only Increases Efficiency But Also Revenues," (with Kevin Breuer and Axel Ockenfels) Working Paper, University of Cologne, February 2020.

"Using Technology to Eliminate Traffic Congestion," (with R. Richard Geddes and Axel Ockenfels) *Journal of Institutional and Theoretical Economics*, 175:1, 126-139, 2019.

"Set Road Charges in Real Time to Ease Traffic," (with R. Richard Geddes and Axel Ockenfels) *Nature*, 23-25, 2 August 2018.

"Markets for Road Use: Eliminating Congestion through Scheduling, Routing, and Real-time Road Pricing," (with R. Richard Geddes and Axel Ockenfels) Working Paper, University of Cologne, January 2018.

"Market Design in Energy and Communications," Working Paper, University of Maryland, April 2015

"Demand Reduction and Inefficiency in Multi-Unit Auctions," (with Lawrence M. Ausubel, Marek Pycia, Marzena Rostek, and Marek Weretka) *Review of Economic Studies*, 81:4, 1366-1400, 2014.

"Applicant Auctions for Internet Top-Level Domains: Resolving Conflicts Efficiently" (with Ulrich Gall, Pacharasut Sujarittanonta, and Robert Wilson), Working Paper, University of Maryland, January 2013.

"Fear of Losing in a Clock Auction" (with Emel Filiz-Ozbay, Erkut Y. Ozbay, and Pacharasut Sujarittanonta), *Review of Economic Design*, 16:2-3, 119-134, 2012.

US Patent No. 8,224,743, "System and Method for a Hybrid Clock and Proxy Auction" (with Lawrence M. Ausubel and Paul Milgrom) issued July 17, 2012.

US Patent No. 8,145,555, "System and Method for the Efficient Clearing of Spectrum Encumbrances" (with Lawrence M. Ausubel and Paul Milgrom) issued March 27, 2012.

"Comparison of Auction Formats for Auctioning Wind Rights" (with Lawrence M. Ausubel) Power Auctions Report for the Bureau of Ocean Energy Management, September 2011.

"Multiple Factor Auction Design for Wind Rights" (with Lawrence M. Ausubel) Power Auctions Report for the Bureau of Ocean Energy Management, September 2011.

"Auction Design for Wind Rights" (with Lawrence M. Ausubel) Power Auctions Report for the Bureau of Ocean Energy Management, August 2011.

"Discrete Clock Auctions: An Experimental Study" (with Emel Filiz-Ozbay, Erkut Ozbay, and Pacharasut Sujarittanonta), *Experimental Economics*, 15:2, 309-322, 2012.

US Patent No. 7,899,734 B2, "System and Method for an Auction of Multiple Types of Items" (with Lawrence M. Ausubel and Wynne P. Jones) issued March 1, 2011.

"Market Design: Harnessing Market Methods to Improve Resource Allocation," White Paper, University of Maryland, October 2010.

"Auctioning Rough Diamonds: A Competitive Sales Process for BHP Billiton's Ekati Diamonds" (with Samuel Dinkin and Robert Wilson). Forthcoming in the *Handbook of Market Design*, Zvika Neeman, Al Roth, and Nir Vulkan (eds.), Oxford University Press. January 2013.

US Patent No. 7,729,975, "System and Method for a Hybrid Clock and Proxy Auction" (with Lawrence M. Ausubel and Paul Milgrom) issued June 1, 2010.

"Pricing Rule in a Clock Auction" (with Pacharasut Sujarittanonta), *Decision Analysis*, 7, 40-57, 2010.

"How Best to Auction Natural Resources," in Philip Daniel, Brenton Goldsworthy, Michael Keen, and Charles McPherson (eds.), *Handbook of Oil, Gas And Mineral Taxation*, Chapter 10, forthcoming, Washington, DC: IMF, 2009.

"Innovation and Market Design." In Josh Lerner and Scott Stern (eds.), *Innovation Policy and the Economy*, Volume 9, National Bureau of Economic Research, 113-137, Chicago: University of Chicago Press, 2009.

"Market Design: Auctions and Matching." In John Siegfried (ed.), *Better Living Through Economics*, Harvard University Press, 223-225, 2010.

"An Overview of Combinatorial Auctions" (with Yoav Shoham and Richard Steinberg), *ACM SIGecom Exchanges*, 7, 3-14, 2007.

"Market-Based Alternatives for Managing Congestion at New York's LaGuardia Airport," (with Michael O. Ball, Lawrence M. Ausubel, Frank Berardino, George Donohue, Mark Hansen, and Karla Hoffman), in *Optimal Use of Scarce Airport Capacity*, Proceedings of AirNeth Annual Conference, The Hague, April 2007.

"Introduction to Combinatorial Auctions," (with Yoav Shoham and Richard Steinberg) in Peter Cramton, Yoav Shoham, and Richard Steinberg (eds.), *Combinatorial Auctions*, 1-13, MIT Press, 2006.

"The Clock-Proxy Auction: A Practical Combinatorial Auction Design," (with Lawrence M. Ausubel and Paul Milgrom) in Peter Cramton, Yoav Shoham, and Richard Steinberg (eds.), *Combinatorial Auctions*, Chapter 5, 115-138, MIT Press, 2006.

"Dynamic Auctions in Procurement," (with Lawrence M. Ausubel) in Nicola Dimitri, Gustavo Piga, and Giancarlo Spagnolo (eds.) *Handbook of Procurement*, Cambridge, England: Cambridge University Press, 2006.

"How Best to Auction Oil Rights," in Macartan Humphreys, Jeffrey D. Sachs, Joseph E. Stiglitz (eds.), *Escaping the Resource Curse*, Chapter 5, 114-151, New York: Columbia University Press, 2007.

"Auctioning Many Divisible Goods," (with Lawrence M. Ausubel) *Journal of the European Economic Association*, 2, 480-493, April-May 2004.

"Vickrey Auctions with Reserve Pricing," (with Lawrence M. Ausubel) *Economic Theory*, 23, 493-505, April 2004. Reprinted in Charalambos Aliprantis, et al. (eds.), *Assets, Beliefs, and Equilibria in Economic Dynamics*, Berlin: Springer-Verlag, 355-368, 2003.

"The Optimality of Being Efficient," (with Lawrence M. Ausubel) Working Paper, University of Maryland, March 2001.

*Maryland Auction Conference*, May 29-31, 1998.

"Ascending Auctions," *European Economic Review*, 42:3-5, 745-756, May 1998.

"Dissolving a Partnership Efficiently," (with Robert Gibbons and Paul Klemperer) *Econometrica*, 55, 615–632, 1987. Reprinted in Paul Klemperer (ed.), *The Economic Theory of Auctions*, Volume 2, Cheltenham, UK: Edward Elgar, 2000.

## Climate policy

*Global Carbon Pricing—The Path to Climate Cooperation* (with David JC MacKay, Axel Ockenfels and Steven Stoft), *MIT Press*, 2017.

"Translating the Collective Climate Goal into a Common Climate Commitment" (with Axel Ockenfels and Jean Tirole), *Review of Environmental Economics and Policy*, 11:1, 165-171, February 2017.

"Price Carbon—I will if you will" (with David JC MacKay, Axel Ockenfels and Steven Stoft), *Nature*, 15 October 2015.

"Symposium on International Climate Negotiations" (with Axel Ockenfels and Steven Stoft), *Economics of Energy & Environmental Policy*, 4:2, 1-64, September 2015.

"An International Carbon-Price Commitment Promotes Cooperation" (with Axel Ockenfels and Steven Stoft), *Economics of Energy & Environmental Policy*, 4:2, 51-64, September 2015.

"Solving the Climate Dilemma" (with David MacKay, Axel Ockenfels and Steven Stoft), carbon-price.com, March 2015.

"How to Negotiate Ambitious Global Emissions Abatement" (with Axel Ockenfels and Steven Stoft), carbon-price.com, May 2013.

"How to Fix the Inefficiency of Global Cap and Trade" (with Steven Stoft), *The Economists' Voice*, 9:1, April 2012.

"Global Climate Games: How Pricing and a Green Fund Foster Cooperation" (with Steven Stoft), *Economics of Energy & Environmental Policy*, 1:2, March 2012. [Appendix, Spreadsheet]

"Kyoto's Climate Game and How to Fix It" (with Steven Stoft), Issue Brief, Global Policy Center, August 2010.

"International Climate Games: From Caps to Cooperation" (with Steven Stoft), Research Paper, Global Energy Policy Center, July 2010.

"Price is a Better Climate Commitment" (with Steven Stoft), *The Economists' Voice*, 7:1, February 2010.

"Global Carbon Pricing: A Better Climate Commitment" (with Steven Stoft), Research Paper, Global Energy Policy Center, December 2009.

"Auctioning Greenhouse Gas Emissions Permits in Australia" (with Regina Betz, Stefan Seifert, and Suzi Kerr), *Australian Journal of Agricultural and Resource Economics*, 54, 219-238, 2010.

"Comments on the RGGI Market Design." Submitted to RGGI, Inc. by ISO New England and NYISO, 15 November 2007.

"Tradeable Carbon Permit Auctions: How and Why to Auction Not Grandfather," (with Suzi Kerr) *Energy Policy*, 30, 333-345, 2002.

"A Review of Markets for Clean Air: The U.S. Acid Rain Program," *Journal of Economic Literature*, 38, 627-633, September 2000.

"The Distributional Effects of Carbon Regulation," (with Suzi Kerr) in Thomas Sterner (ed.) *The Market and the Environment*, Cheltenham, United Kingdom: Edward Elgar, chapter 12, 1999.

## Spectrum auctions

"The German 4G Spectrum Auction: Design and Behaviour" (with Axel Ockenfels), *Economic Journal*, 127, F305-F324, October 2017.

"Open Access Wireless Markets" (with Linda Doyle), *Telecommunications Policy*, 41:5-6, 379-390, June 2017.

"An Open Access Wireless Market" (with Linda Doyle), Working Paper, University of Maryland, March 2016.

"Design of the Reverse Auction in the Broadcast Incentive Auction" (with Hector Lopez, David Malec and Pacharasut Sujarittanonta), Working Paper, University of Maryland, 12 March 2015; Appendix.

"Bidding and Prices in the AWS-3 Auction" (with Pacharasut Sujarittanonta), Working Paper, University of Maryland, May 2015.

"Spectrum Auction Design," *Review of Industrial Organization*, 42:2, 161-190, March 2013.

"Quadratic Core-Selecting Payment Rules for Combinatorial Auctions" (with Robert Day), *Operations Research*, 60:3, 588-603, 2012.

"Activity Rules for the Combinatorial Clock Auction" (with Lawrence M. Ausubel), Working Paper, University of Maryland, November 2011.

"Incentive Auctions and Spectrum Policy," Testimony of Peter Cramton before the United States House Committee on Energy and Commerce, 15 July 2011. [Responses to questions]

"Incentive Auctions," Working Paper, University of Maryland, April 2011.

"Using Spectrum Auctions to Enhance Competition in Wireless Services" (with Evan Kwerel, Gregory Rosston, and Andrzej Skrzypacz), *Journal of Law and Economics*, 54:4, S167-S188, 2011.

"Auctioning the Digital Dividend," in Jan Kramer and Stefan Seifert (eds.), *Communications Regulation in the Age of Digital Convergence: Legal and Economic Perspectives*, Karlsruhe, Germany: Karlsruhe Institute of Technology, 2009.

"A Review of the 10-40 GHz Auction," Office of Communications, United Kingdom, September 2008.

"A Review of the L-Band Auction," Office of Communications, United Kingdom, September 2008.

"The 700 MHz Spectrum Auction: An Opportunity to Protect Competition In a Consolidating Industry" (with Andrzej Skrzypacz and Robert Wilson), submitted to the U.S. Department of Justice, Antitrust Division, 13 November 2007.

"Comments on the FCC's Proposed Competitive Bidding Procedures for Auction 73" (with Gregory Rosston, Andrzej Skrzypacz, and Robert Wilson), 31 August 2007.

"The Effect of Incumbent Bidding in Set-Aside Auctions: An Analysis of Prices in the Closed and Open Segments of FCC Auction 35" (with Allan T. Ingraham and Hal J. Singer) *Telecommunications Policy*, 32, 273-290, 2008.

Economist Letter to NTIA on 700 MHz Spectrum Auction (with Andrzej Skrzypacz, Simon Wilkie, and Robert Wilson), 30 July 2007.

"Essential Entry: Revenues in the 700 MHz Spectrum Auction," University of Maryland, 13 July 2007.

"Revenues in the 700 MHz Spectrum Auction" (with Andrzej Skrzypacz and Robert Wilson), Working Paper, University of Maryland, 27 June 2007.

"Economic Comments on the Design of the 700 MHz Spectrum Auction" (with Andrzej Skrzypacz and Robert Wilson), submitted with testimony of James L. Barksdale to the U.S. Senate Committee on Commerce, Science, and Transportation, 14 June 2007.

"Simultaneous Ascending Auctions," in Peter Cramton, Yoav Shoham, and Richard Steinberg (eds.), *Combinatorial Auctions*, Chapter 4, 99-114, MIT Press, 2006.

"Collusive Bidding in the FCC Spectrum Auctions," (with Jesse Schwartz) *Contributions to Economic Analysis & Policy*, 1:1, 2002.

"Spectrum Auctions," in Martin Cave, Sumit Majumdar, and Ingo Vogelsang, eds., *Handbook of Telecommunications Economics*, Amsterdam: Elsevier Science B.V., Chapter 14, 605-639, 2002.

"How Affirmative Action at the FCC Auctions Decreased the Deficit," (with Ian Ayres) in Ian Ayres, ed., *Pervasive Prejudice? Unconventional Evidence of Race and Gender Discrimination*, Chicago: University of Chicago Press, 315-395, 2001.

"Lessons Learned from the UK 3G Spectrum Auction." In U.K. National Audit Office Report, The Auction of Radio Spectrum for the Third Generation of Mobile Telephones, Appendix 3, October 2001.

"Collusive Bidding: Lessons from the FCC Spectrum Auctions," (with Jesse Schwartz) *Journal of Regulatory Economics*, 17, 229-252, May 2000.

*Simultaneous Ascending Auctions with Package Bidding*, (with John McMillan, Paul Milgrom, Bradley Miller, Bridger Mitchell, Daniel Vincent, and Robert Wilson) Report to the Federal Communications Commission, March 1998.

"Efficient Relocation of Spectrum Incumbents," (with Evan Kwerel and John Williams) *Journal of Law and Economics*, 41, 647-675, October 1998.

"The Efficiency of the FCC Spectrum Auctions," *Journal of Law and Economics*, 41, 727-736, October 1998.

*Package Bidding for Spectrum Licenses*, (with John McMillan, Paul Milgrom, Bradley Miller, Bridger Mitchell, Daniel Vincent, and Robert Wilson) Report to the Federal Communications Commission, October 1997.

*Auction Design Enhancements for Non-Combinatorial Auctions*, (with John McMillan, Paul Milgrom, Bradley Miller, Bridger Mitchell, Daniel Vincent, and Robert Wilson) Report to the Federal Communications Commission, September 1997.

"Synergies in Wireless Telephony: Evidence from the Broadband PCS Auctions," (with Lawrence M. Ausubel, R. Preston McAfee, and John McMillan) *Journal of Economics and Management Strategy*, 6:3, 497-527, 1997.

"Deficit Reduction Through Diversity: How Affirmative Action at the FCC Increased Auction Competition," (with Ian Ayres) *Stanford Law Review*, 48:4, 761-815, 1996.

"The FCC Spectrum Auctions: An Early Assessment," *Journal of Economics and Management Strategy*, 6:3, 431-495, 1997. Reprinted in Donald L. Alexander (ed.), *Telecommunications Policy*, Praeger Publishers, 1997.

"Money Out of Thin Air: The Nationwide Narrowband PCS Auction," *Journal of Economics and Management Strategy*, 4, 267–343, 1995.

"The Case for Affirmative Auction: From Conscience to Coffers," (with Ian Ayres) *New York Times*, 21 May 1995, F13.

**Electricity market design**

"Lessons from the 2021 Texas Electricity Crisis," *Utility Dive*, 23 March 2021.

"Hitting the Jackpot at Texans' Expense," *Dallas Morning News*, 8a, 6 Apr 2021.

"Commentary: My monthly electric bill in Texas would be $250. In California, it is $1,000. Here's why." *San Diego Union-Tribune*, 1 September 2020.

"Electricity Market Design," *Oxford Review of Economic Policy*, 33:4, 589-612, November 2017.

"Capacity Market Fundamentals" (with Axel Ockenfels and Steven Stoft), *Economics of Energy & Environmental Policy*, 2:2, September 2013.

"Economics and Design of Capacity Markets for the Power Sector" (with Axel Ockenfels) *Zeitschrift für Energiewirtschaft*, 36:113-134, 2012.

"Ökonomik und Design von Kapazitätsmärkten im Stromsekto" (with Axel Ockenfels), *Energiewirtschaftlichen Tagesfragen*, 61:9, 14-15, 2011.

*Wind Energy in Colombia: A Framework for Market Entry* (with Walter Vergara, Alejandro Deeb, Natsuko Toba, and Irene Leino) The World Bank, Washington, DC, July 2010.

"Using Forward Markets to Improve Electricity Market Design" (with Lawrence M. Ausubel), *Utilities Policy*, 18, 195-200, 2010.

"Virtual Power Plant Auctions" (with Lawrence M. Ausubel), *Utilities Policy*, 18, 201-208, 2010.

"Prediction Markets to Forecast Electricity Demand" (with Luciano I. de Castro), Working Paper, University of Maryland, August 2009.

"Auctioning Long-term Gas Contracts in Colombia," Working Paper, University of Maryland, September 2008.

"Forward Reliability Markets: Less Risk, Less Market Power, More Efficiency" (with Steven Stoft) *Utilities Policy*, 16, 194-201, 2008.

"Colombia's Forward Energy Market," Working Paper, University of Maryland, August 2007.

"Product Design for Colombia's Regulated Market," Working Paper, University of Maryland, June 2007.

"Colombia Firm Energy Market," (with Steven Stoft), *Proceedings of the Hawaii International Conference on System Sciences*, January 2007.

"Simulation of the Colombian Firm Energy Market," (with Steven Stoft and Jeffrey West), Working Paper, University of Maryland, December 2006.

"Why We Need to Stick with Uniform-Price Auctions in Electricity Markets," (with Steven Stoft), *Electricity Journal*, 20:1, 26-37, 2007.

"The Convergence of Market Designs for Adequate Generating Capacity," (with Steven Stoft), White Paper, California Electricity Oversight Board, April 2006.

"New England's Forward Capacity Auction," University of Maryland, June 2006.

"A Capacity Market that Makes Sense," (with Steven Stoft) *Electricity Journal*, 18, 43-54, August/September 2005.

"Review of the Proposed Reserve Markets in New England," (with Hung-po Chao and Robert Wilson) White Paper, Market Design Inc., January 2005.

"Competitive Bidding Behavior in Uniform-Price Auction Markets," *Proceedings of the Hawaii International Conference on System Sciences*, January 2004.

"Competitive Bidding Behavior in Uniform-Price Auction Markets," Report before the Federal Energy Regulatory Commission, March 2003.

"Rebuttal Addendum: Assessment of Submissions of the California Parties," Report before the Federal Energy Regulatory Commission, March 2003.

"Electricity Market Design: The Good, the Bad, and the Ugly," *Proceedings of the Hawaii International Conference on System Sciences*, January, 2003.

"Pricing in the California Power Exchange Electricity Market: Should California Switch from Uniform Pricing to Pay-as-Bid Pricing?" (with Alfred E. Kahn, Robert H. Porter, and Richard D. Tabors), Blue Ribbon Panel Report, California Power Exchange, January 2001.

"Uniform Pricing or Pay-as-Bid Pricing: A Dilemma for California and Beyond," (with Alfred E. Kahn, Robert H. Porter, and Richard D. Tabors), *Electricity Journal*, 70-79, July 2001.

"Eliminating the Flaws in New England's Reserve Markets," (with Jeffrey Lien) Working Paper, University of Maryland, March 2000.

"Review of the Reserves and Operable Capability Markets: New England's Experience in the First Four Months," White Paper, Market Design Inc., November 1999.

"The Role of the ISO in U.S. Electricity Markets: A Review of Restructuring in California and PJM," (with Lisa Cameron) *Electricity Journal*, 71-81, April 1999.

"A Review of ISO New England's Proposed Market Rules," (with Robert Wilson) White Paper, Market Design Inc., September 1998.

"Auction Design for Standard Offer Service," (with Andrew Parece and Robert Wilson) Working Paper, University of Maryland, July 1997.

"Using Auctions to Divest Generation Assets," (with Lisa J. Cameron and Robert Wilson) *Electricity Journal*, 10:10, 22-31, December 1997.

---

### Financial market design

“Smart Markets for Financial Securities: From Block to Flow Trading” (with Eric Budish, Albert S. Kyle, Jeongmin Lee, David Malac, and David C. Parkes), University of Cologne, August 2018.

“The High-Frequency Trading Arms Race: Frequent Batch Auctions as a Market Design Response,” (with Eric Budish and John Shim), *Quarterly Journal of Economics*, 130:4, 1547–1621, November 2015.

“Implementation Details for Frequent Batch Auctions: Slowing Down Markets to the Blink of an Eye” (with Eric Budish and John Shim), *American Economic Review P&P*, 104:5, 418-424, May 2014.

“Common-Value Auctions with Liquidity Needs: An Experimental Test of a Troubled Assets Reverse Auction” (with Lawrence M. Ausubel, Emel Filiz-Ozbay, Nathaniel Higgins, Erkut Ozbay, and Andrew Stocking). Forthcoming in the *Handbook of Market Design*, Zvika Neeman, Al Roth, and Nir Vulkan (eds.), Oxford University Press. January 2013.

“A Two-Sided Auction for Legacy Loans” (with Lawrence M. Ausubel), University of Maryland, March 2009.

“Making Sense of the Aggregator Bank” (with Lawrence M. Ausubel), *The Economists' Voice,* 6:3, February 2009.

“No Substitute for the 'P'-Word in Financial Rescue” (with Lawrence M. Ausubel), *The Economists' Voice,* 6:2, February 2009.

“Auctions for Injecting Bank Capital” (with Lawrence M. Ausubel), Addendum to A Troubled Asset Reverse Auction, University of Maryland, October 2008.

“A Troubled Asset Reverse Auction” (with Lawrence M. Ausubel), Working Paper, University of Maryland, September 2008.

“Auction Design Critical for Rescue Plan” (with Lawrence M. Ausubel), *The Economists' Voice*, 5:5, September 2008.

*National media on financial rescue plan*

*Print:* “Gaming the Financial System,” *Newsweek*, 18 November 2008.

“Economists Look at Ways to Structure Auctions,” *Wall Street Journal*, 25 September 2008.

“Auctions May Be Only Option for U.S. Bailout,” *Reuters*, 22 September 2008.

*Radio:* “How about Taking Bids on Bad Assets?” *National Public Radio Marketplace*, 2 February 2009.

“Study Suggests Buying Toxic Assets Could Work,” *National Public Radio All Things Considered*, 18 November 2008.

“Complicated Reverse Auction May Aid In Bailout,” National Public Radio Morning Edition, 10 October 2008.

*TV:* “Geithner to Unveil Financial Rescue Plan Monday,” *PBS Nightly Business Report*, 6 February 2009.

“Will the Government Take Away the Toxicity on Bank Books?,” *PBS Nightly Business Report*, 29 January 2009.

“What Price Should Fed Pay” *CBS Evening News*, 23 September 2008.

“Auctioning Securities,” (with Lawrence M. Ausubel) Working Paper, University of Maryland, March 1998.

“Auctions and Takeovers,” *New Palgrave Dictionary of Economics and the Law*, Peter Neuman (ed.), London: MacMillan Press, 1, 122-125, 1998.

“Using Auction Theory to Inform Takeover Regulation,” (with Alan Schwartz) *Journal of Law, Economics, and Organization*, 7, 27–53, 1991.

---

### Medicare auctions and how to fix them

“Designed to Fail: The Medicare Auction for Durable Medical Equipment” (with Sean Ellermeyer and Brett E. Katzman) *Economic Inquiry*, 53:1, 469-485, 2014.

"Medicare Auction Reform," Testimony of Peter Cramton before the United States House Committee on Small Business, 11 September 2012. [Oral Testimony, Transcript of Hearing, Comments of Peter Cramton]

---

**Research on Bargaining**

"Bargaining with a Shared Interest: The Impact of Employee Stock Ownership Plans on Labor Disputes," (with Hamid Mehran and Joseph Tracy) Working Paper, University of Maryland, March 2015.

"Unions, Bargaining and Strikes," (with Joseph S. Tracy) in John T. Addison and Claus Schnabel, eds., *International Handbook of Trade Unions*, Cheltenham, UK: Edward Elgar, Chapter 4, 86-117, 2003.

"Bargaining with Incomplete Information," (with Lawrence M. Ausubel and Raymond J. Deneckere), Robert J. Aumann and Sergiu Hart, eds., *Handbook of Game Theory*, Vol. 3, Amsterdam: Elsevier Science B.V., Chapter 50, 1897-1945, 2002.

"The Effect of Collective Bargaining Legislation on Strikes and Wages," (with Morley Gunderson and Joseph S. Tracy) *Review of Economics and Statistics*, 81:3, 475-487, 1999.

"Impacts of Strike Replacement Bans in Canada," (with Morley Gunderson and Joseph S. Tracy), *Labor Law Journal*, 50:3, 173-179, Fall 1999.

"The Use of Strike Replacements in Union Contract Negotiations: the U.S. Experience 1980–1989," (with Joseph S. Tracy) *Journal of Labor Economics*, 16:4, 667-701, 1998.

"Efficient Relocation of Spectrum Incumbents," (with Evan Kwerel and John Williams) *Journal of Law and Economics*, 41, 647-675, October 1998.

"Deception and Mutual Trust: A Reply to Strudler," (with J. Gregory Dees) *Journal of Business Ethics*, 5, 813–822, 1995. Reprinted in Carrie Menkel-Meadow and Michael Wheeler (eds.), *What's Fair*, John Wiley & Sons, 2004.

"Wage Bargaining with Time-Varying Threats," (with Joseph S. Tracy), *Journal of Labor Economics*, 12, 594–617, 1994.

"The Determinants of U.S. Labor Disputes," (with Joseph S. Tracy), *Journal of Labor Economics*, 12, 180–209, 1994.

"Promoting Honesty in Negotiation: An Exercise in Practical Ethics," (with J. Gregory Dees) *Business Ethics Quarterly*, 3, 359-394, 1993. Reprinted in Patricia Werhane and Tom Donalson, *Ethical Issues in Business: A Philosophical Approach*, Prentice-Hall, 1996, and Carrie Menkel-Meadow and Michael Wheeler (eds.), *What's Fair*, John Wiley & Sons, 2004.

"Strikes and Holdouts in Wage Bargaining: Theory and Data," (with Joseph S. Tracy) *American Economic Review*, 82, 100–121, 1992. Reprinted in Bengt Holmstrom, Paul Milgrom, and Alvin E. Roth (eds.), *Game Theory in the Tradition of Bob Wilson*, Berkeley Electronic Press, May 2002.

"Strategic Delay in Bargaining with Two-Sided Uncertainty," *Review of Economic Studies*, 59, 205–225, 1992.

"Dynamic Bargaining with Transaction Costs," *Management Science***,** 37, 1221–1233, 1991.

"Shrewd Bargaining on the Moral Frontier: Toward a Theory of Morality in Practice," (with J. Gregory Dees) *Business Ethics Quarterly*, 1, 135-167, 1991.

"Sequential Bargaining Mechanisms," in *Game-Theoretic Models of Bargaining*, Alvin Roth (ed.), Cambridge University Press, Chapter 8, 149–179, 1985.

"Bargaining with Incomplete Information: An Infinite-Horizon Model with Two-Sided Uncertainty," *Review of Economic Studies*, 51, 579–593, 1984.

**Other Research**

"Ratifiable Mechanisms: Learning from Disagreement," (with Thomas R. Palfrey) *Games and Economic Behavior*, 10, 255–283, 1995.

"Relational Investing and Agency Theory," (with Ian Ayres) *Cardozo Law Review*, 15, 1033–1066, 1994.

"Cartel Enforcement with Uncertainty About Costs," (with Thomas R. Palfrey) *International Economic Review*, 31, 17–47, 1990. Reprinted in Stephen W. Salant and Margaret C. Levenstein (eds.), *Cartels*, Volume 1, Cheltenham, UK: Edward Elgar, 2005.

"Nonrandom Mixing Models of HIV Transmission," (with Edward Kaplan, and A. David Paltiel) in *Mathematical and Statistical Approaches to AIDS Epidemiology*, edited by Carlos Castillo-Chávez, *Lecture Notes in Biomathematics Series*, Springer-Verlag, 218–239, 1989.

**Research Grants**

"Testbed Experiments for CRP Auction Design," US Department of Agriculture, September 2013 to September 2018, $191,000.

"Design and Experimental Testing of Land Use Mechanisms: Auctions and Coexistence," US Department of Agriculture, June 2015 to September 2017, $52,000.

"Common Value Auctions with Liquidity Needs," National Science Foundation, September 2009 to August 2013, $400,000.

"Dynamic Matching Mechanisms," National Science Foundation, August 2005 to July 2008, $264,188.

"Slot Auctions for U.S. Airports," Federal Aviation Administration, Department of Transportation, September 2004 to August 2005, $309,729.

"Rapid Response Electronic Markets for Time-Sensitive Goods," National Science Foundation, July 2002 to June 2005, $2,000,000.

"Multiple-Item Auctions," National Science Foundation, July 2001 to June 2004, $313,872.

"Auctions for Multiple Items," National Science Foundation, April 1998 to March 2001, $318,175.

"Auctions and Infrastructure Conference," National Science Foundation, April 1998 to March 1999, $25,000.

"Auctions and Infrastructure," World Bank, March-June 1998, $25,000.

"Applying Strategic Bargaining Models to Union Contract Negotiations," National Science Foundation, April 1995 to March 1998, $143,637.

"Applying Strategic Bargaining Models to Union Contract Negotiations," National Science Foundation, April 1992 to March 1994, $177,760.

"Strikes and Delays in Wage Bargaining: Theory and Data," National Science Foundation, April 1990 to March 1992, $153,407.

"Gaming Exercises in Negotiation and Dispute Resolution," National Institute of Dispute Resolution, July to August 1988, $6,000.

"The Role of Time and Information in Bargaining," National Science Foundation, July 1986 to June 1988, $40,000.

"Public Sector Cases on Negotiation," Mellon Foundation, July to August 1985, $12,000.

**Editorial and Public Service**

*Management Science*, Associate Editor, 2018-present.

*Games*, Editorial Board, 2020-present.

Panelist, National Science Foundation, Enhanced Access to Radio Spectrum, 2012-2013.

*Journal of Industrial Economics*, Associate Editor, 1998-2007.

Member, RTO Futures (a working group of economists, executives, and government leaders to address critical issues in electricity restructuring), 2000-2007.

Panelist, National Science Foundation, Economics, 1999-2002.

Panelist, National Science Foundation, Electricity Power System Efficiency and Security, 2002.

Program Committee Chair, *North American Econometric Society Summer Meetings*, June 21-24, 2001.

Panelist, National Science Foundation, Knowledge and Distributed Intelligence, 1998.

**Referee for**

American Economic Review, American Political Science Review, Cambridge University Press, Econometrica, Economic Inquiry, Economic J, Economic Letters, Economic Theory, Energy J, Games & Economic Behavior, Group Decision & Negotiation, International Economic Review, International J of Game Theory, J of Business, J of Business & Economic Statistics, J of Conflict Resolution, J of Economic Theory, J of Economic Surveys, J of Economics & Management Strategy, J of Industrial Economics, J of Labor Economics, J of Law and Economics, J of Law, Economics & Organization, J of Political Economy, J of Public Economics, J of Regulatory Economics, Labour Economics, Management Science, Mathematical Social Sciences, Marketing Science, MIT Press, National Institute for Dispute Resolution, National Science Foundation, Omega, Operations Research, OPSEARCH, Quarterly J of Economics, Rand J of Economics, Research in Experimental Economics, Review of Economic Studies, Scandinavian J of Economics, Science, Social Choice & Welfare, Southern Economic J.

**Recent Post-Docs (Initial Placement)**

Darrell Hoy, April 2014-June 2017 (Tremor Technologies)
David Malec, June 2013-June 2018 (Tremor Technologies)

**Recent PhD Committees Chaired (Initial Placement)**

Hector Lopez, July 2015 (Rivada Networks)
Pacharasut Sujarittanonta, July 2010 (Morgan State University)
Nathaniel Higgins, December 2009 (USDA Economic Research Service)
Matias Herrera Dappe, May 2009 (Bates White)
Andrew Stocking, August 2009 (Congressional Budget Office)
Dipan Ghosh, May 2008 (CRA International)
Martin Ranger, May 2005 (Indiana University)
Jeffrey Lien, August 2001 (US Department of Justice)
Allan Ingraham, May 2001 (Criterion Auctions)
Jesse Schwartz, August 1999 (Vanderbilt University)
Laurent Martin, July 1999 (University of Washington)

**Entrepreneurship**

Founder, Cramton Associates, a consultancy providing expert advice in high-stakes auction markets. 1993 to present.

Director and Chief Economist, Tremor Technologies, a company developing a smart market for reinsurance. 2017 to present.

Chair, Market Design Inc. (with Lawrence Ausubel, R. Preston McAfee, Paul Milgrom, Alvin Roth, and Robert Wilson), a consulting firm that works with governments and companies in designing and implementing state-of-the-art auction and matching methods, 1995 to 2016 (President since 1999, Chair since 2003). Major projects:

- Design auction market for rough diamonds.
- Design auction and suggest market reforms for British Columbia timber market.
- Design and implement virtual power plant auctions in France and Belgium.
- Design and implement auction to sell gas capacity in Germany and France.
- Design and implement U.K. auction to procure greenhouse gas emission reductions.
- Design and implement of spectrum auctions in U.S., Canada, Mexico, Australia, and the U.K.
- Design and implement electricity auctions in North America and South America.

- Design auctions to divest electricity generation plants and power purchase agreements in U.S. and Canada.

Founder, Criterion Auctions, a consulting firm that provides auction support services to governments and companies in high-stake auctions. December 2000 to June 2007.

Chair and Founder, Spectrum Exchange (with Lawrence Ausubel, Paul Milgrom, and Market Design Inc.), a firm to create value for the public by promoting the efficient exchange of spectrum. 1999 to 2009.

**Expert Reports, Affidavits, and Testimony**

"Design of the Reverse Auction in the Broadcast Incentive Auction" (with Hector Lopez, David Malec and Pacharasut Sujarittanonta), Working Paper, University of Maryland, 12 March 2015; Appendix. Filed by EOBC at the FCC.

"Bidding and Prices in the AWS-3 Auction" (with Pacharasut Sujarittanonta), Working Paper, University of Maryland, May 2015. Filed by the Competitive Carriers Association.

ISO New England, Docket Nos. ER14-1050-000, -001, Federal Energy Regulatory Commission, "Prepared Testimony of Peter Cramton on Behalf of ISO New England," January 2014. Comments on ISO New England's proposed Pay For Performance reforms to the Forward Capacity Market.

ISO New England, Docket Nos. ER14-1050-000, -001, Federal Energy Regulatory Commission, "Supplemental Prepared Testimony of Peter Cramton on Behalf of ISO New England," February 2014. Comments on NEPOOL's critique of ISO New England's proposed Pay For Performance reforms to the Forward Capacity Market.

"The Revenue Impact of Competition Policy in the FCC Incentive Auction," December 2013. Comments on the revenue impact of spectrum-aggregation limits in the FCC's incentive auction. On behalf of T-Mobile USA.

"The Rationale for Spectrum Limits and Their Impact on Auction Outcomes," August 2013. Argues that well-crafted spectrum aggregation limits can increase competition both in the market for mobile broadband services and in the spectrum auctions in which they apply. On behalf of T-Mobile USA.

ISO New England and New England Power Pool, Docket No. ER12, Federal Energy Regulatory Commission, "Testimony of Peter Cramton," April 2012. Examines the New England regulation market and proposes an alternative market design. For ISO New England.

Verizon Wireless spectrum transaction with SpectrumCo and Cox, Federal Communications Commission, WT Docket No. 12-4, "Supplemental Declaration of Peter Cramton." March 2012. Supplemental declaration on the FCC's spectrum screen used to evaluate spectrum transactions. On behalf of T-Mobile US.

Verizon Wireless spectrum transaction with SpectrumCo and Cox, Federal Communications Commission, WT Docket No. 12-4, "Declaration of Peter Cramton." February 2012. Declaration on the FCC's spectrum screen used to evaluate spectrum transactions. On behalf of T-Mobile US.

"700 MHz Device Flexibility Promotes Competition," July 2010. Argues that the carrier-specific band plans proposed by AT&T and Verizon Wireless for the 700 MHz paired spectrum will undermine competition. On behalf of the Rural Cellular Association.

"Foreword to Ross Baldick's 'Single Clearing Price in Electricity Markets'," Compete Coalition, www.competecoalition.com, February 2009. Argues that consumers and suppliers are better off with the clearing-price auction in electricity markets.

"Report on Key Design Elements of Auctions Under Australia's Carbon Pollution Reduction Scheme," Tradeslot Report to Australian Department of Climate Change, 26 October 2008.

DC Energy, LLC v. HQ Energy Services (US) Inc., Docket No. EL07-67-000, Federal Energy Regulatory Commission, "Affidavit of Peter Cramton." August 2007. Affidavit arguing that HQ manipulated the NYISO TCC and day-ahead energy markets. On behalf of DC Energy, LLC.

The People of the State of Illinois, et al., Docket No. EL07-47-000, Federal Energy Regulatory Commission, "Affidavit of Peter Cramton." June 2007. Affidavit arguing that the Illinois auction for energy for small customers was a competitive auction. On behalf of J. Aron & Company and Morgan Stanley Capital Group Inc.

Australia National Emissions Trading Taskforce, "Possible Design for a Greenhouse Gas Emissions Trading System," August 2007.

700 MHz Auction, Federal Communications Commission, "Why Large Licenses are Best for the 700 MHz Spectrum Auction." April 2007. On behalf of Verizon Wireless.

New York Independent System Operator, Docket No. ER07-360-000, Federal Energy Regulatory Commission, "Affidavit of Peter Cramton." February 2007. Affidavit identifying manipulation of New York's capacity market by KeySpan and the need for market monitoring and mitigation. On behalf of Consolidated Edison Company of New York.

United States vs. Mario Gabelli. Expert report showing the damages caused by Gabelli's false claims in FCC spectrum auctions. The case was settled in June 2006. Gabelli paid $130 million in damages. On behalf of the United States.

Devon Power LLC, et al., Docket No. ER03-563-030, Federal Energy Regulatory Commission, "Affidavit of Peter Cramton," March 2006. Affidavit in support of the settlement agreement defining the New England Forward Capacity Market. For ISO New England.

AWS Auction, Federal Communications Commission, "Declaration of Peter Cramton." February 2006. Declaration on various auction rules for the AWS auction. On behalf of T-Mobile US.

AWS Auction, Federal Communications Commission, "Reply Declaration of Peter Cramton." February 2006. Reply declaration on various auction rules for the AWS auction. On behalf of T-Mobile US.

AWS Auction, Federal Communications Commission, "Ex Parte of Peter Cramton." March 2006. Ex parte communication on various auction rules for the AWS auction. On behalf of T-Mobile US.

MDI retained as Auction Manager for virtual divestiture of 2,600 MW of nuclear energy as part of the proposed merger between Exelon and PSEG. August 2005.

US-Canada Softwood Lumber Trade Dispute, "Competitive Auction Markets in British Columbia" (with Susan Athey). December 2005. White Paper, Market Design Inc. On behalf of British Columbia Ministry of Forests.

US-Canada Softwood Lumber Trade Dispute, "Comments on DOC Notice of Preliminary Results of Countervailing Duty Review" (with Susan Athey). July 2005. White Paper, Market Design Inc. On behalf of British Columbia Ministry of Forests.

US-Canada Softwood Lumber Trade Dispute, "Competitive Auction Markets in British Columbia" (with Susan Athey). February 2004. White Paper, Market Design Inc. On behalf of British Columbia Ministry of Forests.

US-Canada Softwood Lumber Trade Dispute, "Upset Pricing in Auction Markets: An Overview" (with Susan Athey and Allan Ingraham). March 2003. White Paper, Market Design Inc. On behalf of British Columbia Ministry of Forests.

US-Canada Softwood Lumber Trade Dispute, "An Analysis of Auction Volume and Market Competition for the Coastal Forest Regions in British Columbia"(with Susan Athey and Allan Ingraham). September 2002. White Paper, Market Design Inc. On behalf of British Columbia Ministry of Forests.

US-Canada Softwood Lumber Trade Dispute, "Reserve Prices, Stumpage Fees, and Efficiency" (with Susan Athey and Allan Ingraham). September 2002. White Paper, Market Design Inc. On behalf of British Columbia Ministry of Forests.

US-Canada Softwood Lumber Trade Dispute, "Auction-Based Timber Pricing and Complementary Market Reforms in British Columbia" (with Susan Athey and Allan Ingraham). March 2002. White Paper, Market Design Inc. On behalf of British Columbia Ministry of Forests.

US-Canada Softwood Lumber Trade Dispute, "Setting the Upset Price in British Columbia Timber Auctions" (with Susan Athey and Allan Ingraham). September 2002. White Paper, Market Design Inc. On behalf of British Columbia Ministry of Forests.

US-Canada Softwood Lumber Trade Dispute, “Auctioning Timber to Maximize Revenues in British Columbia” (with Susan Athey and Allan Ingraham). June 2002. White Paper, Market Design Inc. On behalf of British Columbia Ministry of Forests.

US-Canada Softwood Lumber Trade Dispute, “A Comparison of Equation-Based and Parity Pricing of Stumpage Fees for British Columbia Timber Under Long-Term Tenures” (with Susan Athey and Allan Ingraham). April 2002. White Paper, Market Design Inc. On behalf of British Columbia Ministry of Forests.

US-Canada Softwood Lumber Trade Dispute, “Testing for Anti-Competitive Bidding in Auction Markets” (with Susan Athey and Allan Ingraham). March 2002. White Paper, Market Design Inc. On behalf of British Columbia Ministry of Forests.

New England Power Pool, Federal Energy Regulatory Commission, “Review of the Proposed Reserve Markets in New England,” (with Hung-po Chao and Robert Wilson) Market Design Inc., January 2005.

U.S. Department of Defense, Services, “Criterion Auctions, December 2003.

Expert Report of Peter Cramton, *D. Lamar Deloach, et al. v. Philip Morris, Inc., et al.*, Civil Action No. 00-CV-1253, United States District Court, Middle District of North Carolina. October 2003. For R.J. Reynolds. Concluded that R.J. Reynolds did not collude in U.S. tobacco auctions during the class period.

Supplier Behavior in California Energy Crisis, Federal Energy Regulatory Commission, Docket Nos. EL00-95-075 and EL00-98-063, “Competitive Bidding Behavior in Uniform-Price Auction Markets,” March 2003. For Duke Energy.

Supplier Behavior in California Energy Crisis, Federal Energy Regulatory Commission, Docket Nos. EL00-95-075 and EL00-98-063, “Rebuttal Addendum: Assessment of Submissions of the California Parties,” March 2003. For Duke Energy.

U.S. Department of Transportation, Docket Nos. FAA–2001–9852, FAA–2001–9854, “Comments on Alternative Policy Options for Managing Capacity and Mitigating Congestion and Delay at LaGuardia Airport,” June 2002. Recommending auctions to manage congestion at LaGuardia.

Verizon Wireless Petition for Permanent Forbearance from CMRS Number Portability, Federal Communications Commission, WT Docket No. 01-184,“Declaration of Peter Cramton,” February 2002. Comments in support of wireless number portability. For Leap Wireless.

ISO New England, Docket No. ER02, Federal Energy Regulatory Commission, “Affidavit of Peter Cramton,” February 2002. Comments on proposed changes to how the energy clearing price is calculated. For ISO New England.

2000 Biennial Regulatory Review Spectrum Aggregation Limits For Commercial Mobile Radio Services, WT Docket No. 01-14, Federal Communications Commission, “Ex Parte Declaration of Peter Cramton,” October 2001. Further comments on the CMRS spectrum cap. For Leap Wireless.

ISO New England, Docket No. EL00-62-015, Federal Energy Regulatory Commission, “Affidavit of Peter Cramton,” June 2001. Comment on modifications to installed capability market. For ISO New England.

2000 Biennial Regulatory Review Spectrum Aggregation Limits For Commercial Mobile Radio Services, WT Docket No. 01-14, Federal Communications Commission, “Declaration of Peter Cramton,” April 2001. Comments on the CMRS spectrum cap. For Leap Wireless.

C and F Block Broadband PCS Auction, Federal Communications Commission, “Declaration of Peter Cramton,” March 2001. Comments on the impact of fronts in the C and F Block Broadband PCS auction.

“Lessons Learned from the UK 3G Spectrum Auction,” May 2001. An export report on the UK 3G Spectrum Auction. For UK National Audit Office.

“Market Effectiveness Assessment,” (with Jeffrey Lien) May 2001. An expert report assessing the effectiveness of the electricity restructuring plan in Ontario. For TransCanada.

First Millennium Communications, Inc. and Barbara Laurence vs. Entravision Communications Company, No. 1420009074, “Expert Report of Peter Cramton,” May 2001. Comment on the value of clearing rights for broadcast television stations 59 to 69. For First Millennium Communications and Barbara Laurence.

Pacific Communications vs. American Wireless, Superior Court of Fulton County, Georgia, No. 2000CV20099, "Reply Declaration of Peter Cramton," April 2001. Further comments on the impact of a delayed sale of spectrum license by Pacific Communication. For American Wireless.

Pacific Communications vs. American Wireless, Superior Court of Fulton County, Georgia, No. 2000CV20099, "Expert Affidavit of Peter Cramton," February 2001. Comments on the impact of a delayed sale of spectrum license by Pacific Communication. For American Wireless.

"Lessons from the United States Spectrum Auctions," Prepared Testimony of Peter Cramton before the United States Senate Budget Committee, February 2000.

New England Power Pool, Docket No. EL00-83-000, Federal Energy Regulatory Commission, "Affidavit of Peter Cramton," July 2000. Comment on deficiency charge in installed capability market. For ISO New England.

NSTAR Services Company vs. New England Power Pool, Docket No. EL00-83-000, Federal Energy Regulatory Commission, "Affidavit of Peter Cramton," June 2000. Further comments on energy price cap as a response to design flaws. For ISO New England.

NSTAR Services Company vs. New England Power Pool, Docket No. EL00-83-000, Federal Energy Regulatory Commission, "Affidavit of Peter Cramton," June 2000. Comments on energy price cap as a response to design flaws. For ISO New England.

New England Power Pool, Docket No. EL00-62-000; ER00-2052-000, Federal Energy Regulatory Commission, "Affidavit of Peter Cramton," May 2000. Comments on installed capability market. For ISO New England.

New England Power Pool, Docket No. ER00-2016-000, Federal Energy Regulatory Commission, "Affidavit of Peter Cramton," April 2000. Comments on one-part vs. three-part bidding in energy market. For ISO New England.

New England Power Pool, Docket No. ER99-4536-000, Federal Energy Regulatory Commission, "Affidavit of Peter Cramton," October 1999. Summary of review of reserves and operable capability markets. For ISO New England.

New England Power Pool, Docket No. OA97-237-000, Federal Energy Regulatory Commission, "Affidavit of Peter Cramton," October 1998. Reply to comments on review of rules. For ISO New England.

New England Power Pool, Docket No. OA97-237-000, Federal Energy Regulatory Commission, "A Review of ISO New England's Proposed Market Rules,"(with Robert Wilson), September 1998. For ISO New England.

Best Digital vs. U.S. West, American Arbitration Association, Denver Office, No. 77 181 00204 97, "Expert Report of Peter C. Cramton," September 1998. Determine the value of spectrum licenses won by Best Digital in the C-block Broadband PCS auction. For Best Digital.

NextWave vs. Antigone and Devco, Petition to Deny License Proceedings, Federal Communications Commission, "Statement on the Effect of NextWave's Participation in the C-block Auction on Antigone and Devco," March 1997. For Antigone and Devco.

NextWave vs. Antigone and Devco, Petition to Deny License Proceedings, Federal Communications Commission, "Reply Statement on the Effect of NextWave's Participation in the C-block Auction on Antigone and Devco," April 1997. For Antigone and Devco.

## Personal

Born on 12 November 1957

Married to Catherine Durnell Cramton

**EXHIBIT PC-2**

Exhibit PC-2

# Using Spectrum Auctions to Enhance Competition in Wireless Services

Peter Cramton *University of Maryland*
Evan Kwerel *Federal Communications Commission*
Gregory Rosston *Stanford University*
Andrzej Skrzypacz *Stanford University*

## Abstract

Spectrum auctions are used by governments to assign and price licenses for wireless communications. Effective auction design recognizes the importance of competition, not only in the auction but also in the downstream market for wireless communications. This paper examines several instruments that regulators can use to enhance competition and thereby improve market outcomes.

## 1. Introduction

Since their introduction in 1994, spectrum auctions have been remarkably successful in assigning and pricing spectrum. The United States has conducted more than 70 auctions to assign thousands of wireless licenses. These licenses have been put to use by wireless operators to create a competitive and rapidly growing wireless industry. Assigning spectrum licenses to private for-profit companies throughout most of the world, including developed and developing countries, has led to rapid development of wireless telecommunications. Indeed, wireless communications have become a factor in economic development. Good spectrum policy and spectrum auctions will play an important role in continued success.

We believe that the primary goal of spectrum policy and spectrum auctions should be economic efficiency—that is, putting the spectrum to its best use. Unfortunately, an auction that awards the spectrum to bidders with the highest

The views expressed are those of the authors and are not those of the Federal Communications Commission. Cramton thanks the National Science Foundation for funding. The authors thank Patrick DeGraba and Martha Stancill for helpful comments. Cramton, Rosston, and Skrzypacz have provided advice to governments and bidders in auctions.

[*Journal of Law and Economics*, vol. 54 (November 2011)]

values may not assure economic efficiency because the bidders' private values for the spectrum may differ from social values as a result of market structure issues (Borenstein 1988). For example, an incumbent will include in its private value not only its use value of the spectrum but also the value of keeping the spectrum from a competitor. Effective policy must recognize competition issues in the downstream market for wireless services.

Coase's (1959, p. 16) advocating of spectrum auctions recognized the importance of addressing competition: "the problem of monopoly is clearly one to be taken seriously." Nonetheless, he wisely focused on the affirmative case for auctions, leaving for later questions about competition as those are important regardless of the spectrum allocation methodology.

This paper examines instruments available to the regulator to address competition issues in both spectrum auctions and the resulting downstream markets for wireless services. These instruments include set-asides, bidding credits, spectrum caps, band plan, auction format, and antitrust enforcement/merger review policy. Each of these instruments, under the right circumstances, can play a role in enhancing competition.

There are, however, no easy answers. The instruments must be used with care to avoid unintended harm. The purpose of this paper is better to understand the properties of the various options. In the end, regulators must rely on judgment in establishing competition policy—a judgment informed by a thorough understanding of the particular setting, practical experience, and how the instruments work.

Perhaps the most important step the government can take to enhance competition is making more spectrum available and making the spectrum available sooner rather than later. Spectrum is an essential input in wireless communications. More spectrum supports more competition. Each spectrum auction is a new opportunity for a potential entrant or a new service and improved coverage. There is strong empirical support for the hypothesis that additional spectrum enhances competition, lowers consumer prices, and increases economic welfare (Hazlett and Munoz 2009).

Our analysis of policy options is not exhaustive. We focus on options that are most closely related to spectrum auctions. Other policies, such as mandatory tower sharing and mandatory roaming, may be desirable for reducing entry barriers and network costs, but we do not address them here.

We begin by discussing the goals of the regulator. Then we discuss the various options available to the regulator to promote competitive goals and give examples. We present models that motivate the need for various instruments and suggest where the instruments are apt to be most effective. Finally, we discuss the use of the methods in actual spectrum auctions.

## 2. Goals

We consider the primary goal of the regulator to be economic efficiency—that is, putting the spectrum to its best use. Best use is defined as assignment of licenses that maximizes the consumer value of wireless services less the cost of producing those services. In the simplest settings (for example, with one license for sale and no incumbents, with bidders that can correctly assess profit opportunities, and with an assumption known as private values), if postauction profits are an increasing function of postauction social value created by the winner, then an ascending auction can achieve an efficient allocation of the license. If a firm expects the highest profit because it will offer a service of especially high consumer value at especially low cost, then awarding the spectrum to the firm with the highest value (and hence the highest willingness to pay) is aligned with maximizing efficiency.

Most spectrum auctions, however, are held in a much more complex environment. In particular, a common asymmetry in the auctions is the distinction between an incumbent and an entrant. The incumbent has existing customers, network infrastructure, and spectrum; the entrant does not. Moreover, the incumbent can potentially limit entry and hence competition by purchasing additional spectrum that would otherwise go to an entrant. The trade-off is not trivial. On one hand, the incumbent may have important economies of scale and scope that would allow it to use the additional spectrum more efficiently. On the other hand, part of the willingness to pay for the incumbent in the auction comes from the value of deterring new entry, which is bad for overall efficiency for the standard market power reasons and may be bad for the dynamic evolution of the service if the threat of competition is necessary to speed up the build out and development of new technologies.

Competition policy seeks to address this potential market failure by encouraging competition in the provision of wireless services. Since licenses are awarded via auctions, to create new entry in the provision of wireless services it is often necessary to first encourage entry into auctions; the expectation that incumbents are likely to have some synergy value for new spectrum and have additional incentives to bid aggressively in the auction to deter entry is often a strong deterrent for potential new bidders.

At the same time, competition policy needs to consider the potential for higher social value resulting from concentrated ownership of spectrum: incumbents may be able to leverage existing infrastructure to provide services more efficiently, and some aggregation of spectrum may be necessary to develop a new generation of services (for example, a high-speed wireless data service). This is a difficult trade-off.

Another goal in many auction settings is raising revenues. A pro-efficiency argument for maximizing revenues is that substituting auction revenues for revenues raised through distortionary taxes saves the deadweight loss of those taxes. Yet maximizing revenues often conflicts with the goal of creating a competitive market for wireless services. First, reducing the amount of available spectrum would typically increase auction revenue, but it restricts the development of wireless services. Second, selling the rights to be a monopolist can raise much more revenue than selling licenses to many competing providers, to the detriment of postauction competition and efficiency.

Our view is that, in practice, the regulators should primarily focus on allocating spectrum efficiently and creating postauction competition in the wireless services market, and they should worry less about revenues. The reason for our view is that wireless communication services typically have large and persistent positive spillovers to the entire economy as well as substantial consumer welfare benefits resulting from both static and dynamic competition (Rosston 2003). Moreover, the demand for wireless services is strong and growing, and the amount of available and usable spectrum is limited. In practice, it means that even without restricting the spectrum or boosting revenues by increasing postauction market power, spectrum auctions lead to high revenues as long as either new entrants are attracted to participate in the auction or incumbents can be enticed to compete for larger quantities of spectrum. Finally, as our examples show, in some cases there may be no trade-off between raising revenue and efficient allocation of spectrum.

Low revenues in the auction are bad if they are the result of a flawed auction design, tacit collusion, or successful entry deterrence by the incumbents. These cases should be a reason for concern. If, at some point in time, the amount of available spectrum becomes large relative to demand, then revenue considerations may become more important. Moreover, the regulator may impose minimum prices for spectrum to assure that the spectrum is used for commercial wireless services only if there are no better alternative uses of the spectrum. Looking at the recent wireless spectrum auctions, we seem to be far away from that point. Therefore, in the rest of the paper, we focus on promoting efficient allocation of spectrum and competition in the wireless services market and not raising auction revenues.

## 3. Policy Instruments to Enhance Competition

Regulators have a variety of options to enhance competition. We discuss six: set-asides, bidding credits, spectrum caps, band plan, auction design, and antitrust enforcement. Typically, each policy option affects competition both in the auction and in the downstream market for wireless services. We focus on how the policy choices affect the overall market efficiency, and hence we consider the effects of competition in the auction mostly in terms of how it will affect post-market conduct via creating or blocking new entry and/or allowing or disallowing efficient aggregation of spectrum.

### 3.1. Set-Asides

The regulator reserves one or more blocks of spectrum for a particular type of bidder. The most common use is to set aside a block of spectrum for new entrants and exclude incumbents (appropriately defined) from bidding on the set-aside block. This approach is highly effective in motivating participation by new entrants, since it guarantees that a new entrant will win at least the set-aside block. But it may result in entry by firms with higher costs and less attractive offerings than incumbents. The approach has been used in auctions in many countries, such as the United States, the United Kingdom, and Canada.

### 3.2. Spectrum Caps

Spectrum caps limit the quantity of spectrum that can be held by an operator in a particular geographic area. Spectrum caps are applied either within the current auction or to a category of spectrum beyond the current auction. For example, in most of the European 3G auctions, bidders could win at most one block. In the United States, before the personal communications service (PCS) auctions in 1994, the Federal Communications Commission (FCC) set a cap for commercial mobile radio spectrum, including both cellular and PCS bands. The spectrum cap approach enables entrants to bid for a greater quantity of newly available spectrum than incumbents. Both spectrum caps and set-asides limit the excessive concentration of spectrum, but their drawback is that they may prohibit efficient aggregation of spectrum.

### 3.3. Bidding Credits

Bidders of a favored type get a percentage discount on any winning bids. For example, new entrants may get a 25 percent bidding credit. In this case, a new entrant submitting a bid of \$100 would have to pay only $(1 - .25) \times \$100 = \$75$ if the bid were to win. Bidding credits typically apply to all blocks on which the favored bidders bid.[1]

### 3.4. Band Plan

The band plan determines how the spectrum is sliced into blocks and partitioned into geographic areas. The band plan impacts competition and the range of services that can be offered. If the service areas are too large, small local operators may be excluded; if the service areas are too small, auction complexity and aggregation/exposure risk make it difficult for a bidder to succeed in aggregating enough licenses for a more expansive business plan. If the licenses are too small in frequency and cannot be easily aggregated, then some broadband services may become infeasible. Coordinating band plans across countries also promotes entry by international providers. It enables more compatible services

---

[1] Bidding credits to encourage new entry are rarely used. The most common use of bidding credits has been in U.S. spectrum auctions, where they are granted to small businesses. See our discussion in Sections 4.4 and 5.3.

and leverages economies of scale in both service provision and hardware manufacturing.

### 3.5. *Auction Design*

Features of the auction design, such as the bid format, the reserve price, and the information policy (for example, anonymous versus transparent bidding), also can influence auction competition. For example, allowing package bids may help bidders aggregate spectrum efficiently. Some auction designs may favor incumbents and help them deter efficient entry. Finally, some designs are more prone to tacit collusion among bidders, which may reduce efficiency if firms refrain from bidding to keep prices low and, hence, prices are not used to select the most efficient providers.

### 3.6. *Antitrust Enforcement*

Antitrust enforcement plays an important role in encouraging competition before, during, and after the auction. Before and during the auction, strict rules again bidder collusion are needed to discourage anticompetitive behavior, so that prices in the auction can guide an efficient allocation. After the auction, antitrust oversight and enforcement can prevent anticompetitive mergers and other firm behavior that undermines competition in the market for wireless services.

## 4. Models of Competition in Spectrum Auctions

As we discussed in the Introduction, in a simple environment an ascending auction allocates the spectrum to the firm that values it the most. Such allocation is good for overall efficiency only if firm valuations are aligned with social values. Yet there are many practical situations in which such a simplistic rule is not optimal. We now discuss some of these practical considerations.

### 4.1. *Firms Are Willing to Pay More for a Monopoly Position*

Consider spectrum for a new service in which two identical licenses are available for auction. A firm can bid for either one or two licenses. Bidding for both licenses has the advantage that the firm, if it wins, secures a monopoly in the new service. Assuming (realistically) that the monopoly profits are more than twice the duopoly profits, one firm is apt to win both licenses. Social welfare, however, may be higher with two firms or with one firm. On one hand, the monopolist is likely to exercise market power after auction (which is inefficient); on the other hand, there may be important cost savings from not having two independent service providers. It is important to note that the inefficiency of a monopolistic provider is often not only due to the static underprovision of service (which could be potentially fixed by rate regulation) but also due to lower competitive pressure to innovate, build out coverage, and develop new services.[2]

If a regulator decides that it is better to avoid creating a monopoly, then all that is required is a spectrum cap limiting each bidder to a maximum quantity of spectrum. Such a solution is common in practice. For example, the U.S. FCC limited licensees in the satellite radio (digital audio radio service) auction to one of the two licenses available, but they subsequently allowed the two licensees to merge.

### 4.2. *Model 1: The Effect of a Set-Aside for New Entrants*

Most spectrum auctions involve incumbents. The new spectrum can go to incumbents or new entrants or both. The asymmetry between incumbents and entrants tilts the auction result toward sustaining the status quo market structure. To illustrate the issues, in the rest of this section we discuss a few simple models of competition in auctions with incumbents and entrants. The models are based on those of Jehiel and Moldovanu (2003).

Suppose first that there is one additional license for sale via an ascending auction. Before the auction, there is one incumbent in the industry who already owns $M$ licenses. Suppose that if there are $k$ firms after the auction, then the profit per license will be $\pi(k)$. Thus, $\pi(1)$ is the monopoly profit per license and $\pi(2)$ is the duopoly profit per license. We assume throughout that $\pi(k)$ is a decreasing function of $k$. We also assume that for small $k$ social welfare is increasing in $k$, and that for large $k$ it is potentially decreasing. These assumptions can be made endogenous using one of the standard models of industry competition, with some economies of scale making the total surplus nonmonotonic in $k$. Essentially, competition transfers existing profits from firms to consumers (via lower markups) and yields efficiency gains from expanded consumption, but it potentially increases costs as additional firms incur fixed costs to provide service.

Assume that all the firms are symmetric, other than the distinction between the new entrants and the incumbent. We assume that there are many potential entrants. Compare the following two scenarios: In scenario A, the incumbent and entrants bid on equal terms. In scenario B, the incumbent is not allowed to bid for the new license; it is set aside for new entrants.

Jehiel and Moldovanu (2003) illustrate the results of such an auction. In scenario A, the incumbent would win the new license at price $p_A = \pi(2)$, and there would remain only the single monopoly firm in the industry. In scenario B, the license would go to one of the new entrants also at a price of $\pi(2)$.[3]

To see the first claim, notice that a new entrant would bid for the license up

---

[2] We admit that from the theoretical point of view, the effect of competition on innovation is ambiguous. Yet casual observations of the telecommunication services industry suggest that competition speeds up innovation.

[3] In all models, the auction format is an ascending clock auction.

to $\pi(2)$, the entrant's postauction profit. If the incumbent does not win the license, then postauction incumbent's total profit is $M\pi(2)$, or $\pi(2)$ per license. Alternatively, if the incumbent wins the new license, then its total profits, gross of the price of that license, are $(M + 1)\pi(1)$. Therefore, the incumbent is willing to pay up to the difference of gross profits between winning and losing:

$$V = (M + 1)\pi(1) - M\pi(2) = \pi(2) + [M + 1][\pi(1) - \pi(2)]. \quad (1)$$

The last expression on the right-hand side is the incumbent's monopoly rent per license, $[\pi(1) - \pi(2)]$ on all $M + 1$ licenses if it succeeds in deterring entry. The incumbent is willing to bid that much more to protect its existing market power.

In the second scenario, the potential entrants would bid the price up to $\pi(2)$. This would result in the same auction revenues as in the first scenario and a more competitive postauction market structure.

We admit that this model, as well as the models presented below, is stylized and does not do justice to the full complexity of spectrum auctions, where firms are asymmetric (beyond the asymmetry between entrants and incumbents), have private information about their business plans and cost structures, and have a value of additional licenses that is not necessarily linear in terms of the number of licenses because of complementarities among different blocks or because of decreasing marginal values of additional licenses. This simple model is intended to highlight only the incumbent bias in auctions that can lead to an inefficient allocation of the licenses as a result of an inefficient postauction market structure. Furthermore, it highlights that revenues in unrestricted auctions do not need to be strictly higher than those in auctions with spectrum caps or set-asides.

One extension of the model is to allow multiple incumbents. Suppose one license is up for auction and there are $k$ incumbents. Competition between the incumbents would drive prices up to $\pi(k)$, and entry would not occur since the entrants would be willing to bid only up to $\pi(k + 1)$. Whether it is efficient to set aside the spectrum would depend on what is more important: having another provider or allowing incumbents to aggregate more spectrum and leverage economies of scale.[4]

### 4.3. *Model 2: Small Auction Participation Costs and Asymmetric Profits*

Now, in addition to the setup of model 1, suppose that there is a small cost $c$ to participate in the auction and that firms differ in their profits per license—that is,

$$\pi_i(k) \neq \pi_j(k),$$

---

[4] If instead $k$ additional licenses are available and there is a limit of one license per bidder, then the incumbents can split the market, and the bidding stops at $\pi(k + 1)$ instead of $\pi(k)$, resulting in no entry and low revenues. This is what happened in the German 1999 spectrum auction. For a model with such a split as the unique equilibrium outcome, see Grimm, Riedel, and Wolfstetter (2003). Such a split can be especially inefficient if the incumbents differ in their ability to use the spectrum efficiently or if it is more efficient to aggregate the spectrum rather than split it.

where $i$ and $j$ represent different firms. It is realistic to assume that these differences are large compared to $c$ but small compared to the effect of the market structure: $\pi_i(k) > \pi_j(k+1)$ for all $i$ and $j$. The differences between $\pi_i(k) \neq \pi_j(k)$ are assumed to be private information before the auction. In addition, the auctioneer sets a small minimum reserve price $P_{\text{MIN}}$ such that $P_{\text{MIN}} < \pi_i(2)$ for every bidder $i$.

Again consider two scenarios: In scenario A, the incumbent and entrants bid on equal terms. In scenario B, the new license is set aside for new entrants. This game is more difficult to analyze because of the participation decision. To simplify, suppose that there are two potential entrants other than the incumbent and that $c$ is small enough that if faced only with competition from another entrant, each entrant is willing to pay the participation cost $c$.[5]

What is the equilibrium outcome now? Subsequent to the participation decisions of the firms, the game is as in model 1. But now, in scenario A, the entrants realize that competition is futile and that hence they are strictly better off not participating in the auction, resulting in very low revenue. In scenario B, the entrants enter and auction revenue is equal to the minimum of their $\pi_i(2)$.

There are two effects for efficiency. First, using the set-aside changes the postauction market structure from a monopoly to duopoly. Second, if one of the new entrants is more efficient than the incumbent, not using the set-aside can lead to a less efficient firm using the new license. This can happen even if the ranking of social efficiency is aligned with the ranking of profits because (1) as we discussed in the previous model, the incumbent has additional reasons to bid aggressively to protect profits from existing licenses, and (2) in our scenario, we assumed that this motive is stronger than any differences in efficiency. Of course, the opposite outcome is also possible: if the incumbent is the more efficient firm and the set-aside is used, the license would be inefficiently allocated to the entrant.

### 4.4. *Model 3: Bidding Credits for New Entrants*

Suppose that there is a single incumbent with one license, one additional license is up for auction, there are many potential entrants, and all firms other than the incumbent are symmetric. The auctioneer offers bidding credits of $x$ percent for all new entrants, so that if the winning price is $p$, then a new entrant would pay only $(1-x)p$. Then a potential entrant is willing to bid up to

$$p = \pi(2)/(1-x) > \pi(2).$$

Bidding credits have two possible impacts on the auction outcome, depending on whether the term $2\pi(1) - [1 + 1/(1-x)]\pi(2)$ is positive or negative.

If the term is positive, then the incumbent will still win the auction because it is willing to bid up to $p = 2\pi(1) - \pi(2)$, while an entrant is willing to bid

---

[5] For a similar model, see Milgrom (2004, sec. 6.3.1).

only up to $\pi(2)/(1 - x)$. The price will be $\pi(2)/(1 - x)$, and the market will remain concentrated. In that case, even though the bidding credits do not affect the market allocation, they do increase revenue from the auction.

If the term is negative, then a new entrant will win the auction and pay a price net of the bidding credit that is $\pi(2)$, so the revenues are not affected.[6] In addition, the market becomes more competitive. As before, if there are costs of participating in the auction, then auction revenues could increase in both cases. Also, as before, if the firms are heterogeneous, bidding credits may reduce efficiency (and revenues) if they make an entrant win the auction when the incumbent is more efficient.

Combining the two cases of model 3, we summarize as follows. If the regulator is interested in finding a balance between maximizing revenues and promoting competition, then bidding credits of moderate size are a win-win situation: they increase revenues without worsening the market structure.[7] As usual, there are many caveats to this analysis. We discuss one, which is a major concern in practice.

The regulator should be worried that a new entrant would use the bidding credit to obtain the license and then resell it, either directly or indirectly via a 100 percent wholesale contract, to the incumbent. Suppose that the incumbent can create an affiliate, or front, that would follow such a strategy, and suppose that $x$ is small enough that without such a strategy the incumbent would win the auction at a price $\pi(2)/(1 - x)$. Instead, it could drop out of the auction and let the front win at the same price but recapture the bidding credit. In this way the incumbent would still end up with the license and pay only $\pi(2)$. Such a strategy can undo any benefits of increased competition. Moreover, creating an opportunity for such rent seeking induces private parties to make socially wasteful expenditures to benefit from the credits. In addition, the regulator must expend resources to determine which parties qualify for the credits. Similar issues arise in the case of set-asides or spectrum caps: firms interested in getting around these restrictions may try to use third parties to meet the requirements legally but then use contracts to violate the intent of the requirements in an economic sense. One possible solution is to use tests similar to the ones used by antitrust agencies in determining market shares to outlaw any contracts that would undo any bidding credits, set-asides, or spectrum caps intended to increase postauction competition. This is not always easy to implement, however, since the regulator may not have as strong a mandate to intervene in contracting as does the competition authority and since such monitoring of firms is complicated.

In practice, improving welfare using either bidding credits or set-asides is

---

[6] If there is only one entrant, then the price net of the bidding credit would be $[2\pi(1) - \pi(2)](1 - x) > \pi(1)(1 - x)$. In that case, revenues go down. To see this, note that the revenues are decreasing in $x$ in this case, and at $x$ such that the incumbent and entrant are willing to bid up to exactly the same price, the revenues are $\pi(2)$, which is the same as without bidding credits.

[7] Milgrom (2004, p. 237) shows another model in which moderate bidding credits improve revenues in the auction.

complicated. For example, when using bidding credits, a commonly advocated solution is to estimate the additional social value of a new entrant in dollars and then give that lump-sum bidding credit to all new entrants. However, such estimates are difficult to obtain. Moreover, it is possible that the additional social value depends on the type of the entrant and also on which of the current incumbents would be the alternative. In that case, a simple credit of a lump sum for all new entrants would not be efficient, and it may not even be possible to achieve the efficient allocation with a simple auction with bidder-specific bidding credits. In addition, should the regulator ever post a number representing the value of an extra entrant, one can expect it to be a source of controversy and lobbying by the interested parties. This may explain why in practice we more often see the regulators imposing spectrum caps or using set-asides rather than using bidding credits.

Spectrum caps, set-asides, and bidding credits can be generalized and combined into a variety of quantity-based and/or price-based instruments. This is most readily done in auctions that optimize across all bids to maximize an objective subject to constraints. Spectrum caps and set-asides are examples of constraints on the bids, but these and other constraints can also be imposed on the outcome. For example, as a constraint on spectrum concentration, one could require that the sum of the squared spectrum shares not exceed a particular level.

## 5. Discussion of Policy Instruments in Practice

### *5.1. Small Business and New Entrant Distinctions*

Before discussing the different competition policy tools, it is important to distinguish the social tools used in the United States to promote other goals. The United States mixes competition and social policy by creating in the auctions a special group of bidders known as designated entities. The FCC's auction authority stemmed from the Omnibus Budget and Reconciliation Act of 1993 (OBRA 1993; Pub. L. No. 103-66; 107 Stat. 312 [1993]). Section 309 of OBRA 1993 provides the FCC's auction authority but also includes several directions for the implementation of auction authority. First, it directs that maximization of revenues shall not be the goal of the auction. In addition, section 309(j) provides that the FCC should ensure the opportunity of small businesses, businesses owned by women and minorities, and rural telephone companies (collectively known as designated entities) to participate in the auction process and in the provision of service. Because of the Supreme Court's decision in *Adarand Constructors, Inc. v. Pena* (515 U.S. 200 [1995]), implementation of the provisions of 309(j) evolved to provide specific incentives to promote small businesses only. In most cases, small businesses have also been new entrants, but not all new entrants to wireless service are small businesses. For example, MCI considered bidding in the first PCS auctions. Although MCI was a large telecommunications provider at the time, it was not a wireless operator and would have been a new entrant into wireless service.

In the major spectrum auctions, the FCC faced a trade-off in trying to comply with the law that true small businesses have a reasonable chance at winning licenses and also have the financial ability to compete in the wireless marketplace. Allowing larger companies to back a small business in a variety of ways and help to provide a source of funding for postauction competition addresses the latter objective while potentially conflicting with the spirit of the small business provisions.

The FCC's initial rules permitted larger telecommunications companies to back certain smaller companies, such as Alaska Native Wireless and Salmon PCS. Some people viewed such companies as fronts for the larger companies. As a result, the FCC tightened the control requirements over time, and fewer small businesses participated in the subsequent auctions. Ultimately, the economic key to small business policies is whether they lead to successful competition in the market for wireless services. These effects are evaluated by ignoring the difficulties with the definition and enforcement of small businesses and by instead looking at the impact on entry and competition. In our opinion, the use of bidding credits for small businesses in the U.S. spectrum actions did not have a major impact on postauction competition.

### *5.2. Set-Asides and Spectrum Caps*

Although set-asides and spectrum caps are not identical, they often serve a similar purpose when the spectrum cap is sufficiently binding on all incumbents: they provide a guarantee that a new entrant will be able to acquire spectrum. One difference is that with set-asides, there typically are specific licenses allocated for new entrants, while with spectrum caps, the auction determines the allocation subject to constraints on the quantity of spectrum for which any single bidder can bid. In addition, set-asides often are a simple way of implementing a spectrum cap that is supposed to apply to the incumbents as a sum rather than individually. For example, if there are 40 MHz of spectrum for sale, with two incumbents, if the regulator wants to guarantee that a new entrant wins at least 10 MHz, the rules can either set aside that 10 MHz or impose a spectrum cap of 15 MHz on each of the incumbents. The second solution has the side effect of imposing a restriction on how the incumbents can split their winnings. A third alternative would be to impose a cap of 30 MHz on the sum of winnings by the incumbents, but that can complicate the rules of the auction more than the set-aside.

The FCC has used both spectrum caps and set-asides. For the broadband PCS A and B blocks, incumbent cellular carriers were prevented from buying in-region licenses because of a 45-MHz spectrum cap. The 25 MHz of cellular spectrum combined with the 30-MHz PCS blocks would have caused them to exceed the cap. However, they could buy the PCS A and B licenses in adjacent markets to expand their geographic footprints. The FCC set aside the broadband

PCS C block for small businesses. The definition of small business precluded most of the incumbent wireless providers from participating in the auction. To qualify, the business had to have less than $125 million in annual revenue and less than $500 million in assets.

In addition to limiting participation in the broadband C-block auction to small businesses, the FCC offered the bidders installment payments: 10 percent down and the rest paid over 10 years. Unfortunately, the top three bidders in the auction declared bankruptcy, and the fourth largest bidder failed to make its down payment. Their bids comprised approximately 75 percent of the $10 billion in C-block net bids.

In 2003, the Supreme Court ruled in favor of NextWave, the largest bidder to declare bankruptcy, with bids of $4.2 billion in the C-block auction (*Federal Communications Commission v. NextWave Personal Communications, Inc.*, 537 U.S. 293 [2003]). The Court ruled that while the firm was reorganizing under bankruptcy protection, the FCC did not have the right to take back its licenses for failure to make payments. The FCC had to return to NextWave the licenses that it had cancelled and subsequently reauctioned. In 2004, as part of settlement with the FCC, NextWave agreed to return 75 percent of its licenses. In 2005, those returned licenses were auctioned by the FCC. Finally, in March 2005, the FCC approved NextWave's $3 billion sale to Verizon of the licenses it did not return to the FCC as part of the settlement. The set-aside and installment payments were intended to promote the "participation in the provision of spectrum-based services" by small businesses (FCC, Second Memorandum Opinion and Order in PP Docket No. 93-253, FCC 94-215, 9 FCC Rcd. 7245, 59 Fed. Reg. 44272, par. 3 [August 26, 1994]). But that objective was hardly achieved, and the public was deprived of the benefits of most of the 30 MHz of spectrum in the C block for almost 10 years.

In the European 3G auctions, regulators used variants of set-asides and spectrum caps.[8] In the United Kingdom, the government auctioned five 3G licenses with four incumbent 2G providers. Each provider was limited to purchasing at most a single 3G license. The fifth license was set aside for a new entrant. In the Netherlands, although there was a limit of a single license per participant, there were five existing 2G providers, so new entrants did not have the same guarantee of a new entrant license. Having the same number of licenses as incumbents limited competition in the auction; however, the end result was that the Netherlands had five providers at the end of the auction, the same number of competitors as the United Kingdom. Switzerland had four incumbents and four licenses, and again prices were extremely low, since the potential new entrants aligned with the incumbents before the bidding began.

Germany imposed a similar spectrum cap, ensuring that at least four firms won licenses. In the end, prices in the German auction were high, and six firms ended up with licenses. Austria used a design similar to that of the Germans

---

[8] Much of the European discussion is based on Klemperer (2004).

and also had six licensees, but it did not have high revenue. In both countries, only four operators ultimately survived.

A lesson from the European 3G auctions is that spectrum caps and set-asides can have a major impact on auction outcomes, but other factors, such as timing and rules against collusion, also play an important role. In addition, the extent of ex post competition can be influenced by the regulator with these instruments, but the underlying economies of scale may well undo the regulator's desire for more competitors.

In the recent Canadian advanced wireless services (AWS) auction, the government used a band plan similar to the U.S. AWS band plan but set aside three blocks for new entrants. The definition of new entrant focused on entry to the nationwide business and ruled out the three largest wireless providers in Canada: Telus, Rogers, and Bell Canada. All others, including existing small regional carriers, were eligible to bid on both the set-aside and non-set-aside blocks in any area of the country. This created competition between the three incumbents in the auction because there were only two large blocks and one small block available in any geographic area for them. The set-aside resulted in at least one new entrant in every area of the country, but the amount of new entry varied by region.

Set-asides and spectrum caps have been used to ensure that new entrants have a chance to provide service and additional competition in the market for wireless service. However, there is a potential sacrifice from set-asides and spectrum caps—the incumbent wireless providers may be the most efficient providers of service. If the sacrifice of efficiency is not outweighed by the additional competition engendered by a new, less efficient competitor, then there is a real cost to using set-asides and spectrum caps. For example, an incumbent provider may be able either to integrate additional spectrum into an existing network to provide additional capacity at low cost or to combine with existing spectrum to provide a new service that requires more capacity than would be possible without the additional spectrum. If the new entrant would not increase competition by innovating or lowering prices but would incur build-out costs and additional operating costs, promoting new entry would not be socially efficient.

Set-asides and spectrum caps should be used when there is a real chance that the additional competition will increase consumer choice and lead to efficient competition. This needs to be determined before using these tools.

### 5.3. *Bidding Credits*

Bidding credits differ from set-asides or binding spectrum caps in that they do not guarantee a new entrant (or small business) winner. In the United States, bidding credits have historically been used for small businesses, but theoretically they could be used for all new entrants. A bidding credit can serve at least two different purposes. Ayres and Cramton (1996) and model 3 described above show that under certain circumstances, the increased competition in the auction due to a bidding credit can increase revenues at the same time that it increases the possibility of a new entrant. A second feature of a bidding credit is that it allows the government to put a value (in either absolute or percentage terms) on having a new entrant. With a set-aside, the government must decide in advance of the auction, without knowing the cost of having a new entrant, whether it wants to set aside a license for a new entrant.

With a bidding credit, the government could decide that it is willing to sacrifice $1 billion in revenues to get a new entrant. In this case, an incumbent would be forced to bid at least $1 billion more than a new entrant to get the license. Similarly, the government could decide that the benefits of a new entrant are worth 25 percent of the license price, and it would be willing to sacrifice that much revenue (although the Ayres and Cramton [1996] analysis shows that this would be an upper bound on the revenue loss).

The maximum cost of a bidding credit is the face value of the credit. For example, a 25 percent bidding credit may be bid away completely if the two most efficient providers of service each qualify for the credit. Instead of bidding $100 for a license without a credit, they would bid up to $133.33, or $100/(1–.25). The net revenue to the government would not change in this circumstance. In FCC auctions, for example, there is evidence that much, if not all, of the bidding credit has been bid away as qualified entities compete for the license. For example, in the FCC's regional narrowband PCS auction, small business bidding credits of 25 percent were available on one of two 50/50-kHz paired licenses and one of three 50/12.5-KHz paired licenses. The net prices for the licenses with bidding credits ended up being slightly higher than the net prices for licenses without bidding credits.

A variant on the bidding credit was the FCC's use of a reserve price to trigger the 700-MHz C-block open-access provisions, which mandated a minimum amount for the licenses but did not reveal the differential between the value of the licenses with and without the open-access provisions. The FCC wanted to impose open-access conditions on the C block but not if the revenue received would be perceived to be too low. As a result, it put a reserve price of $4.64 billion in auction 73 on the C block with the requirement that if the reserve price were met, the licensee would be required to comply with the open-access provisions (and if the reserve were not met, the block would be reauctioned without these provisions). The reserve price can be seen as meeting a political challenge because the FCC did not allow bids for the license without the open-access provision (akin to allowing bids with and without a bidding credit). This is a variant of a bidding credit because it differentially provides advantages to a provider willing to comply with open-access provisions.[9]

---

[9] See Brusco, Lopomo, and Marx (2011) for an analysis of how bidding credits can outperform such a contingent reauction design.

### *5.4. Spectrum Availability and Band Plan*

Perhaps the most important issue in spectrum auctions and wireless competition is the amount of spectrum available to the market (Hazlett and Munoz 2009). To provide wireless communication, providers need a combination of spectrum, technology, and capital (such as cell sites and back haul). With less spectrum, providing the same amount of service generally requires more advanced technology and more investment in capital, such as more cell sites. While auctions tend to garner headlines because of the billions of dollars raised, a successful spectrum policy would result in low prices for spectrum because the supply would be large enough that the scarcity value would be reduced. Such a policy conflicts with the frequent government objective of increasing short-term government revenues.

In the U.S. broadband PCS auctions, the initial band plan had two big blocks of spectrum and four smaller nonadjacent blocks of spectrum. In early 1994, the FCC reformulated the band plan and was able instead to have three large blocks of spectrum and three smaller blocks all in adjacent frequencies. This change to the band plan increased the effective number of viable license winners and also made the licenses more substitutable, thereby increasing competition in the auction and in the aftermarket for wireless service.

### *5.5. Auction Format*

Much has been written about different ways to auction spectrum. The focus of this paper is designing auctions to maximize the chance that licenses are assigned efficiently. With the substantial uncertainty regarding the efficient assignment and valuations by different bidders, there are different auction formats that can be used to achieve efficiency. However, there also are auction formats that some governments have adopted that are unlikely to achieve an efficient allocation of licenses. For example, the initial spectrum auctions in New Zealand, as discussed in Milgrom (2004) and McMillan (1994), were not well designed, and the experience from these auctions helped the FCC avoid similar inefficiency and negative public perceptions (Kwerel and Rosston 2000).

In 1994, the FCC adopted the novel simultaneous multiple-round (SMR) auction. In an SMR auction, all licenses are up for bid at the same time and the auction does not close until bidding ends on all licenses. In some versions of the rules, bidders choose bid prices, while in others the auctioneer runs a price clock for each license and bidders select the licenses or packages of licenses on which they wish to bid (with the prices going up for licenses with excess demand). The SMR design facilitates pursuing efficient backup strategies among substitutable licenses and aggregation of complementary licenses. The auction process is aided by activity rules that require the bidders to bid on a minimum amount of spectrum[10] each round to maintain their eligibility to bid in future

---

[10] For the purpose of auction eligibility rules, the FCC measures the spectrum associated with license as the product of bandwidth and population (that is, MHz-pops).

rounds. Before the auction begins, bidders put up money to acquire an initial maximum eligibility level. If the bidder does not meet the required activity, its maximum eligibility is reduced. Over the course of the auction, the required activity level increases. These measures are intended to ensure that bidders do not hold back on bidding until very late in the auction. For more specific details of the auction design, see McMillan (1994).

Although this auction format had many benefits and worked well (Ausubel et al. 1997; McMillan 1994; Milgrom 2004), there were a few problems with the format. Some of the problems, such as potential tacit collusion and fat-finger bidding (inadvertently entering the wrong bid amount), were easily solved with minor changes to the auction systems (Kwerel and Rosston 2000). Others, such as the exposure problem, required more changes to the auction format and rules. A bidder might suffer from potential exposure if its business plan requires the aggregation of multiple licenses. For example, if it is successful in acquiring only a portion of the required licenses, it might end up losing money by paying too high a price for the final pieces of its package, by stopping bidding and being stuck with an insufficient set of licenses, or by paying a bid withdrawal penalty to drop the incomplete package of licenses. Fear of this outcome could cause the bidder to reduce its initial bids or even not bid at all. To address the exposure problem, the FCC has used limited combinatorial or package bidding in two auctions. In the first—auction 51 for regional narrowband PCS—there was only a single round of bidding and there were no nonpackage bids, so the system was not tested in a rigorous manner.

In its recent 700-MHz auction (auction 73), the FCC used package bidding on the C block. The auction provided for package bidding on three predefined packages of licenses in the C block: (1) the 50 States package containing the eight Regional Economic Area Grouping (REAG) licenses comprising the continental United States, Alaska, and Hawaii, (2) the Atlantic package containing the two REAG licenses comprising Puerto Rico, the U.S. Virgin Islands, and the Gulf of Mexico, and (3) the Pacific package containing the two REAG licenses comprising the U.S. Pacific territories. As it turned out, there were few package bids during the auction. Ultimately, only a single package was won: the Pacific package. Google was the only party bidding on the 50 States package, and it stopped bidding when the open-access reserve price was reached. For Google, as a new entrant with no existing spectrum holdings and seeking nationwide coverage and to trigger the C-block open-access provisions, the availability of a nationwide package may have been important to its participation in the auction.

Bazelon (2009) argues that the C block was not the best choice for implementing package bidding because the license size for the C block was relatively large. Instead, the exposure risk was probably greater on other blocks available in the auction that had smaller geographic license areas. In addition, the use of a package bid for one block when there are other substitute blocks created substantial strategic issues in the auction. Brusco, Lopomo, and Marx (2009) and Bazelon (2009) discuss how Verizon was able to use the eligibility rules strategically to pay a much lower price for the C block than if there had been a more efficient auction design. With a more efficient design, it is possible that auction participants other than Verizon would have acquired more licenses—that is, they were willing to pay more for C-block licenses than Verizon paid. Yet since the auction eligibility rules prevented them from moving from the other blocks to the C block, they were unable to compete for the C-block spectrum. As a result, the C-block licenses sold for substantially less than comparable aggregations of spectrum in the other blocks.[11]

Many other countries have adopted auction formats similar to the FCC's standard SMR auction. For example, Canada has used the SMR format. One significant difference between large countries (for example, United States, Canada, and India) and smaller countries is that large countries typically are divided into many small license areas, whereas many other countries award nationwide licenses. Auctioning nationwide licenses can help reduce the geographic exposure problem and make running the auction more straightforward, but it makes it more difficult for a business with a plan to serve a small area to acquire spectrum.

Sweden adopted a novel format for its 2008 auction. It allowed bidders to withdraw bids from specific licenses without a bid withdrawal penalty, so long as they bid on another license. This withdrawal rule may make sense when all of the licenses in an auction are substitutes, as were most of the licenses in the Swedish auction. In that way, if the price of a specific license is out of line with substitutes, then bidders can bid on the substitute licenses. Ultimately, there should not be much difference in the license prices. However, when some of the licenses are not good substitutes, the lack of a withdrawal penalty can create strategic incentives. In the Swedish auctions, 12 of the licenses were very similar (they were all paired spectrum), two others were similar to the 12 but had guard band considerations, and one license was not similar. This dissimilar license was unpaired spectrum suitable for time division duplex (TDD) technology, whereas the others were paired spectrum suitable for frequency division duplex (FDD) technology. As a result, a bidder could bid on the 14 FDD licenses and not reveal its true demand for a TDD license until the end of the auction, without pushing up the price of the TDD license. If bidders have budget constraints and competitors want both a paired and an unpaired license, bidding on the paired licenses to drive up the price of the paired licenses before competing for the unpaired license (or vice versa) could be a reasonable strategy. But that might result in an inefficient allocation of licenses.

In the Canadian AWS auction in 2008, most of the auction was for AWS spectrum. However, in each geographic area, the government also included licenses for PCS and 1670-MHz spectrum. These licenses generally were not substitutable for the AWS licenses (nor were they complementary in the sense that they could not really be combined to provide a wider band service). As a result, at times bidders used them to park eligibility during the auction, because they

---

[11] The C block also had open-access provisions that may account for some of the price difference.

were a relatively cheap place to maintain eligibility points. This ultimately caused the prices for those licenses to be higher than they would have been, and it possibly caused some to go unsold (for example, if a bidder was interested in buying a large number of those licenses to cover a large geographical area, he could be discouraged from doing so if he saw that some of the licenses got expensive for strategic reasons not related to the value of these licenses).

Beginning in 2008, the United Kingdom adopted the package clock auction for its spectrum auctions (Ausubel et al. 2006; Cramton 2009). This auction allows package bids but retains the simple price discovery of the SMR auction by starting with an initial clock stage where bidders express their demand for licenses as the auctioneer raises prices. The Netherlands, Denmark, and Austria also adopted the package clock auction design. A key innovation of the design is that it allows a technology-neutral auction, where the auction configures the spectrum band plan for either (or both) devices or technologies that require paired spectrum blocks (long-term evolution [LTE]) or those that do not (worldwide interoperability for microwave access [WiMAX]). Allowing different technologies to compete in the auction requires a package auction in which bidders bid on packages of lots. The design includes an innovative pricing rule and activity rule, both of which tend to reduce strategic bidding and improve price discovery. As with all package auctions, this design may favor bidders bidding on larger packages.

In general, the lessons from spectrum auctions are that it is beneficial to include in the same auction either substitutable licenses or nearly substitutable licenses and to auction complementary licenses in a way that makes it easier for bidders to resolve the exposure problem. Including nonrelated licenses (neither substitutes nor complements) in the same auction does not tend to increase efficiency and may create strategic incentives during the auction that ultimately end up reducing the efficiency of allocation of licenses.

### *5.6. Antitrust Enforcement and Regulation*

Antitrust enforcement is a key feature of competition policy. However, it generally is not a useful tool to prevent the creation of excessive spectrum concentration in auctions. To run an efficient auction, bids must be sincere. If after the close of an auction, a bidder could not acquire a license because of antitrust enforcement, that could impair the efficiency of the auction process. For example, if an incumbent was able to rescind its bid because of antitrust enforcement, it would have an incentive to hold up the auction process by winning and expecting either to be granted a license or to be denied a license and not be forced to pay its bid. In the second circumstance, it would be able to delay competition and/or raise the costs of its rivals. If the firm were required to pay its bid and then to spin off its new holding (or to pay a bid withdrawal penalty and have the government reauction the license), it still might find it worthwhile to delay competition while it challenged the antitrust authorities.

There are at least three important roles for antitrust: in ex ante auction rules, as discussed above with regard to spectrum caps; in the auctions, to prevent collusion among bidders; and in the marketplace, for wireless services.

Ex ante auction rules generally come from the regulatory agency rather than from the antitrust authority. However, there are times where the antitrust authority works with the regulator to ensure a competitive auction, which is an appropriate and effective role. Preventing collusion between bidders during an auction is extremely important to efficiency and revenue and to the overall integrity of the spectrum auction process. Antitrust authorities may face difficult decisions about allowing or preventing preauction agreements between potential competitors.

Most antitrust scrutiny will come after the conclusion of the license assignment process (whether by auction or some other method). For example, there have been a large number of wireless mergers. Generally, the mergers are of two types: geographic extension mergers and within-area consolidation mergers. Usually the geographic extension mergers cause no competitive concern because they replace one provider with another and do not remove any competitors. Consolidation mergers usually generate more antitrust scrutiny. There can be efficiency justification for such mergers: the additional spectrum controlled by a single company can increase its technological flexibility. At the same time, there can also be an excessive concentration of market power with regard to spectrum or wireless services that causes a concern. Usually such concerns can be solved with targeted divestitures.

There is also a role for the regulation of the interconnection of wireless services to promote efficient competition. Competitors need to work together to provide network service, and as such they may not agree on efficient levels of intercarrier compensation. For example, few people would have adopted wireless service in the United States had they not been able to connect to traditional wire-line telephones. Initially, many of the wire-line companies and their state regulators viewed wireless as a service for the rich, and they used it to provide income for the traditional landline companies. Calls from wireless phones to landline phones were typically charged 3 cents per minute for termination on the landline network. However, calls to wireless callers did not receive symmetric treatment; in fact, the wireless provider often had to pay the landline provider the same 3 cents per minute even though the call was going the other direction and even though the wireless provider was incurring the cost of terminating the call. The FCC's implementation of the 1996 Telecommunications Act interpreted reciprocal termination as symmetric termination rates. This simple regulatory intervention nearly immediately reduced termination rates overall to less than a penny a minute and even less over time. As a result, wireless companies offer plans with free nights and weekends that would have been cost prohibitive without the change in termination rates.

Ensuring that bidders in auctions know that they will have the ability to interconnect with incumbent providers at reasonable and symmetric rates makes it more likely that a new entrant can build a viable business and thus more likely that a potential new entrant would attempt to enter. This, in turn, will increase competition in the auction for licenses.

## 6. Conclusion

Well-designed spectrum auctions can play an important role in fostering a competitive wireless industry. Of even greater importance is the quantity of spectrum made available for wireless services. Spectrum is an essential input. The more spectrum allocated to wireless services, the more competition can be sustained. Other regulatory policies, including rules for interconnection, number portability, tower sharing, and roaming, also affect the competitiveness of the market for wireless services.

Spectrum auctions provide a fast and effective means of assigning spectrum to wireless operators. We believe that the primary objective of these auctions should be efficiency—putting the spectrum in the hands of those best able to use it—not raising revenue. Efficient auctions raise substantial revenues, and focusing more on revenues likely distorts the outcome away from social welfare maximization.

We have discussed a number of instruments that can be used by the regulator to enhance competition, both in the auction and in the market for wireless services. These include spectrum caps, bidding credits, and set asides. Experience with these instruments has been mixed. In some cases they worked well in promoting social welfare, such as the initial spectrum cap in the U.S. broadband market. In other cases, such as the programs to benefit small businesses in the U.S. C-block PCS auction, the result was lengthy delay in the use of the spectrum because of subsequent bankruptcy and litigation. Our conclusion is that these instruments must be used with care. The phrase attributed to the Hippocratic Oath very much applies: first, do no harm.

## References

Ausubel, Lawrence, Peter Cramton, R. Preston McAfee, and John McMillan. 1997. Synergies in Wireless Telephony: Evidence from the Broadband PCS Auctions. *Journal of Economics and Management Strategy* 6:497–527.

Ausubel, Lawrence, Peter Cramton, and Paul Milgrom. 2006. The Clock-Proxy Auction: A Practical Combinatorial Auction Design. Pp. 115–38 in *Combinatorial Auctions*, edited by Peter Cramton, Yoav Shoham, and Richard Steinberg. Cambridge, Mass.: MIT Press.

Ayres, Ian, and Peter Cramton. 1996. Deficit Reduction through Diversity: How Affirmative Action at the FCC Increased Auction Competition. *Stanford Law Review* 48: 761–815.

Bazelon, Coleman. 2009. Too Many Goals: Problems with the 700 MHz Auction. *Information, Economics, and Policy* 21:115–27.

Borenstein, Severin. 1988. On the Efficiency of Competitive Markets for Operating Licenses. *Quarterly Journal of Economics* 103:357–85.

Brusco, Sandro, Giuseppe Lopomo, and Leslie Marx. 2009. The "Google Effect" in the FCC's 700 MHz Auction. *Information, Economics, and Policy* 21:101–14.

———. 2011. The Economics of Contingent Re-auctions. *American Economic Journal: Microeconomics* 3:165–93.

Coase, R. H. 1959. The Federal Communications Commission. *Journal of Law and Economics* 2:1–40.

Cramton, Peter. 2009. Spectrum Auction Design. Working paper. University of Maryland, Department of Economics, College Park.

Grimm, Veronika, Frank Riedel, and Elmar Wolfstetter. 2003. Low Price Equilibrium in Multi-unit Auctions: The GSM Spectrum Auction in Germany. *International Journal of Industrial Organization* 21:1557–69.

Hazlett, Thomas, and Roberto Munoz. 2009. A Welfare Analysis of Spectrum Allocation Policies. *RAND Journal of Economics* 40:424–54.

Jehiel, Phillippe, and Benny Moldovanu. 2003. An Economic Perspective on Auctions. *Economic Policy* 36:269–308.

Klemperer, Paul. 2004. *Auctions: Theory and Practice.* Princeton, N.J.: Princeton University Press.

Kwerel, Evan, and Gregory Rosston. 2000. An Insiders' View of FCC Spectrum Auctions. *Journal of Regulatory Economics* 17:3:253–89.

McMillan, John. 1994. Selling Spectrum Rights. *Journal of Economic Perspectives* 8:145–62.

Milgrom, Paul. 2004. *Putting Auction Theory to Work.* Cambridge: Cambridge University Press.

Rosston, Gregory. 2003. The Long and Winding Road: The FCC Paves the Path with Good Intentions. *Telecommunications Policy* 27:501–15.

EXHIBIT PC-3

Exhibit PC-3

# Dissolving a Partnership Efficiently

Peter Cramton; Robert Gibbons; Paul Klemperer

*Econometrica*, Vol. 55, No. 3. (May, 1987), pp. 615-632.

*Econometrica*, Vol. 55, No. 3 (May, 1987), 615-632

# DISSOLVING A PARTNERSHIP EFFICIENTLY

BY PETER CRAMTON, ROBERT GIBBONS, AND PAUL KLEMPERER[1]

Several partners jointly own an asset that may be traded among them. Each partner has a valuation for the asset; the valuations are known privately and drawn independently from a common probability distribution. We characterize the set of all incentive-compatible and interim-individually-rational trading mechanisms, and give a simple necessary and sufficient condition for such mechanisms to dissolve the partnership ex post efficiently. A bidding game is constructed that achieves such dissolution whenever it is possible. Despite incomplete information about the valuation of the asset, a partnership can be dissolved ex post efficiently provided no single partner owns too large a share; this contrasts with Myerson and Satterthwaite's result that ex post efficiency cannot be achieved when the asset is owned by a single party.

KEYWORDS: Mechanism design, efficient trading, fair division, auctions, public goods.

## 1. INTRODUCTION

WHEN A PARTNERSHIP IS TO BE DISSOLVED, who should buy out his associates and at what price? When municipalities jointly need a hazardous-waste dump, which town should provide the site and how much should it be compensated by the others? When husband and wife divorce, or children divide an estate, who should keep the family house or farm, and how much should the others be paid?

We consider partnerships in which each player $i$ is endowed with a share $r_i$ of a good to be traded, and specific capital or other transaction costs make it inefficient to sell the good on the market and split the proceeds.[2] We look for procedures that allocate the good ex post efficiently while satisfying interim individual rationality. Unlike Myerson and Satterthwaite (1983)—who show that no procedure can yield both properties in two-player bargaining games with uncertainty ($r_1 = 1$ and $r_2 = 0$)—we show that the distributed ownership found in a partnership often makes the two compatible. For the case of $n$ players whose valuations are independently drawn from an arbitrary distribution, we derive a simple condition that is necessary and sufficient for efficient, individually-rational dissolution, and we introduce a simple bidding game that will accomplish such dissolution whenever it can be achieved as a Bayesian Nash equilibrium in some extensive-form game.

The application that inspired our analysis was the Federal Communication Commission's allocation of licenses for cellular-telephone franchises. After closing the list of applicants, the FCC proposed to make the final allocation using

---

[1] This project was begun at Stanford University and financially supported by the Sloan Foundation, the National Science Foundation, and the Center for Economic Policy Research. We are grateful to David Gold for posing the problem and encouraging its analysis, and to Roger Guesnerie, Christopher Harris, David Kreps, Robert Wilson, and two referees for helpful suggestions.

[2] See van Damme (1985) for a related study of fair division when each player has an equal ownership share.

a simple lottery. Prior to the lottery each applicant has an equal chance of winning, and so can be thought of as owning a $1/n$ share in the license. Our analysis suggests that the applicants would do better to form a cartel (that would win the lottery with certainty) and then allocate the franchise to one of their number via our bidding game; this is more efficient than the lottery, even if the winner is permitted to resell. A similar example is the Federal Aviation Administration's proposal to allocate landing slots at busy airports by lottery. Again, a more efficient approach is to assign the airlines shares in the slot equal to their weights in the proposed lottery, and let them play the bidding game we propose.

As another application of the theory, consider the following buy-out provision of many two-member partnerships: one side submits a "buy-out" offer, and the other side then has the choice of either buying or selling at these terms. Since this scheme does not guarantee ex-post efficiency (the first player will not, in general, submit his valuation, so the object will be inefficiently allocated if the other's valuation is between the first player's bid and valuation), it too can be improved upon by our bidding game.

The bidding game that achieves efficient, individually-rational dissolution differs from a typical auction in that every player pays or receives a sum of money that is a function of all the players' bids. Moreover, the set of bidders who pay a positive amount typically is not limited to the winning bidder, but includes the second and other high bidders as well. Since such bidding arrangements are not frequently observed, we determine the circumstances in which more common auctions—such as first- and second-price—can achieve efficient, individually-rational dissolution. This part of our analysis was inspired by Samuelson (1985), who describes a similar problem and solves a two-player example in which types are drawn from a uniform distribution on $[0, 1]$. He finds that split-the-difference bidding (the average of first- and second-price) yields an efficient allocation, but he ignores the individual rationality constraint that players should prefer participation in the game to retaining their current share. (He imposes instead the weaker constraint that players prefer participation to being dispossessed of their current share.) We consider $n$ players and arbitrary distributions and show that this and other similar auctions may accomplish efficient, individually-rational dissolution, but only when partners' shares are very close to equal.

Samuelson also provides an interesting interpretation of his work as an exploration of the Coase Theorem under incomplete information: instead of the complete-information conclusion that efficiency is always achieved and that property rights are immaterial, he shows that efficiency may be lost and property rights may matter. In these terms, our analysis shows exactly when efficiency can be achieved and how property rights matter.

The rest of the paper is organized as follows. In Sections 2 and 3, we analyze a revelation game to determine the set of partnerships that can be dissolved efficiently. Section 4 introduces a bidding game, that accomplishes efficient dissolution whenever it is possible, and Section 5 characterizes the set of partnerships for which efficient dissolution is possible. Section 6 shows that commonly observed auctions are efficient in some circumstances.

## 2. THE REVELATION GAME

Our model has $n$ players indexed by $i \in N = \{1, \ldots, n\}$. Player $i$ owns a share $r_i$ of the good to be traded ($r_i \in [0, 1]$ and $\sum_{i=1}^{n} r_i = 1$) and has a valuation for the entire good of $v_i$. Each player's valuation is known privately, but it is common knowledge that the valuations are drawn independently from a distribution $F$ with support $[\underline{v}, \bar{v}]$ and positive continuous density $f$.

We consider the direct revelation game in which players simultaneously report their valuations $v = \{v_1, \ldots, v_n\}$ and then receive an allocation $s(v) = \{s_1(v), \ldots, s_n(v)\}$ and $t(v) = \{t_1(v), \ldots, t_n(v)\}$, where $s_i$ is the ownership share and $t_i$ is the net money transfer to player $i$. (Since this allocation is trader-specific, it may depend on the vector of initial ownership rights, $r = \{r_1, \ldots, r_n\}$.) We require that these allocations balance: $\sum s_i(v) = 1$ and $\sum t_i(v) = 0$ for all $v \in [\underline{v}, \bar{v}]^n$. The pair of outcome functions $\langle s, t \rangle$ is referred to as a *trading mechanism.*

A player with valuation $v_i$, share $r_i$, and money $m_i$ has utility $v_i r_i + m_i$, which is linear in money and the asset. Also, we assume that each player is endowed with enough money, say $\bar{v}$, that any required transfer is feasible. Because of the linear utility, only net transfers matter, so player $i$'s utility before participating in the trading mechanism $\langle s, t \rangle$ can be taken to be $v_i r_i$, while afterwards it is $v_i s_i + t_i$. Let $-i = N \backslash i$ and let $\mathscr{E}_{-i}\{\cdot\}$ be the expectation operator with respect to $v_{-i}$. Then we can define the expected share and money transfer for player $i$ when he announces $v_i$ by

$$S_i(v_i) = \mathscr{E}_{-i}\{s_i(v)\} \quad \text{and} \quad T_i(v_i) = \mathscr{E}_{-i}\{t_i(v)\},$$

so the player's expected payoff is

$$U_i(v_i) = v_i S_i(v_i) + T_i(v_i).$$

The mechanism $\langle s, t \rangle$ is *incentive compatible* if all types of all players want to report their private information truthfully:

$$U_i(v_i) \geqslant v_i S_i(u) + T_i(u) \quad \forall i \in N,\ v_i,\ u \in [\underline{v}, \bar{v}].$$

By the *Revelation Principle* (Myerson (1979), among others), we lose no generality by restricting attention to incentive-compatible mechanisms. The mechanism $\langle s, t \rangle$ is interim *individually rational* if all types of all players are better off participating in the mechanism (in terms of their expected payoff) than holding their initial endowments:

$$U_i(v_i) \geqslant r_i v_i \quad \forall i \in N \quad \text{and} \quad v_i \in [\underline{v}, \bar{v}].$$

The following lemmas develop a necessary and sufficient condition for a mechanism to be incentive compatible and individually rational. Since the proofs are either simple or standard, they are relegated to the Appendix.

LEMMA 1: *The trading mechanism $\langle s, t \rangle$ is incentive compatible if and only if for every $i \in N$, $S_i$ is increasing and*

$$\text{(IC)} \qquad T_i(v_i^*) - T_i(v_i) = \int_{v_i^*}^{v_i} u \, dS_i(u)$$

*for all $v_i$, $v_i^* \in [\underline{v}, \bar{v}]$.*

Lemma 1 follows from the fact that utility is linear in money and the asset. Linearity implies that $U_i$ is convex and increasing in $v_i$, with derivative $S_i$ almost everywhere. The continuity of $U_i$ implies that the net utility $U_i(v_i)-r_iv_i$ has a minimum over $v_i \in [\underline{v}, \bar{v}]$. Lemma 2 identifies this worst-off type, and this allows us to restate individual rationality as a single condition in Lemma 3.

LEMMA 2: *Given an incentive-compatible mechanism* $\langle s, t\rangle$ *trader i's net utility is minimized at* $v_i^* = \frac{1}{2}[\inf(V_i^*)+\sup(V_i^*)] \in [\underline{v}, \bar{v}]$, *where*

$$V_i^* = \{v_i \mid S_i(u) < r_i \ \forall\, u < v_i;\ S_i(w) > r_i \ \forall\, w > v_i\}.$$

In the simplest case, $S_i$ is continuous and has $r_i$ in its range, so the valuation of the worst-off type satisfies $S_i(v_i^*) = r_i$; that is, the worst-off type expects to receive a share equal to his initial ownership right $r_i$. Intuitively, the worst-off type expects on average to be neither a buyer nor a seller of the asset, and therefore he has no incentive to overstate or understate his valuation. Hence, he does not need to be compensated in order to induce him to report his valuation truthfully, which is why he is the worst-off type of trader.

This in an interesting generalization of a similar result in Myerson and Satterthwaite (1983) for bilateral exchange ($r=\{0,1\}$). In their paper, the lowest-type buyer ($\underline{v}$) and the highest-type seller ($\bar{v}$) are worst off; here the worst-off type typically is between $\underline{v}$ and $\bar{v}$, since it is no longer clear who is selling and who is buying.

LEMMA 3: *An incentive-compatible mechanism* $\langle s, t\rangle$ *is individually rational if and only if for all* $i \in N$

$$\text{(IR)} \qquad T_i(v_i^*) \geq 0,$$

*where* $v_i^*$ *is defined in Lemma* 2.

Lemmas 1–3 lead to a necessary and sufficient condition for a trading mechanism to be incentive compatible and individually rational, stated in Lemma 4 below.

LEMMA 4: *For any share function s such that* $S_i$ *is increasing for all* $i \in N$, *there exists a transfer function t such that* $\langle s, t\rangle$ *is incentive compatible and individually rational if and only if*

$$\text{(I)} \qquad \sum_{i=1}^{n}\left[\int_{v_i^*}^{\bar{v}}[1-F(u)]u\,dS_i(u) - \int_{\underline{v}}^{v_i^*} F(u)u\,dS_i(u)\right] \geq 0,$$

*where* $v_i^*$ *is defined in Lemma* 2.

The "only if" part of the lemma follows directly from the previous lemmas and the budget balance conditions $\sum s_i(v)=1$ and $\sum t_i(v)=0$, which every feasible mechanism must satisfy. The "if" part of the lemma is proven by constructing a transfer function $t$ that is incentive compatible and individually rational provided the inequality (I) holds. The proof makes the following intuition precise: there exists a transfer rule $t$ that entices the worst-off type of each trader to participate in the mechanism, because (I) guarantees that the expected gains from trade are sufficient to bribe every trader to tell the truth.

## 3. EX POST EFFICIENCY

The trading mechanism $\langle s, t\rangle$ is *ex post efficient* if for each vector of valuations $v$ the outcome of the mechanism $\{s(v), t(v)\}$ is Pareto-undominated by any alternative allocation, ignoring incentive constraints.[3] Thus, ex post efficiency requires that the asset go to the trader with the highest valuation. A partnership $\langle r, F\rangle$ can be *dissolved efficiently* if there exists an ex post efficient trading mechanism $\langle s, t\rangle$ that is incentive compatible and individually rational. Such a mechanism will be said to *dissolve* the partnership. For economy of expression, we will henceforth refer to ex post-efficient mechanisms that are incentive compatible and individually rational as *efficient trading mechanisms.* A partnership that can be dissolved efficiently will be referred to as a *dissolvable* partnership.

We are now prepared to answer the central question of this paper: What partnerships can be dissolved efficiently? At first glance, one might think that the set of dissolvable partnerships is empty; that is, the incomplete information about valuations necessarily leads to some inefficiency in trade. This is not the case. The following theorem gives a necessary and sufficient condition for the existence of an efficient trading mechanism.

THEOREM 1: *A partnership with ownership rights r and valuations independently drawn from F can be dissolved efficiently if and only if*

$$\text{(D)} \qquad \sum_{i=1}^{n}\left[\int_{v_i^*}^{\bar{v}}[1-F(u)]u\,dG(u)-\int_{\underline{v}}^{v_i^*}F(u)u\,dG(u)\right]\geqslant 0,$$

*where* $v_i^* = F^{-1}(r_i^{1/n-1})$ *and* $G(v_i)=F(v_i)^{n-1}$.

PROOF: Ex post efficiency requires that the good go to the trader who values it the most:

$$s_i(v)=\begin{cases}0 & \text{if} \quad v_i<\max v_j,\\ 1 & \text{if} \quad v_i=\max v_j.\end{cases}$$

(In the event that two or more traders have the highest valuation, then the shares can be split arbitrarily among them. Since ties occur with zero probability, they will be ignored in what follows.) By independence, the expected share function $S_i$ is given by

$$S_i(v_i)=\Pr\{v_i>\max_{j\neq i} v_j\}=F(v_i)^{n-1}=G(v_i).$$

Thus, $v_i^*$ satisfies $F(v_i^*)^{n-1}=r_i$, so $v_i^*=F^{-1}(r_i^{1/n-1})$. Substituting into (I) of Lemma 4 yields (D). *Q.E.D.*

---

[3] Our definition of ex post efficiency corresponds to classical ex post efficiency as defined in Holmstrom and Myerson (1983), since incentive constraints are ignored.

## 4. AN EFFICIENT BIDDING GAME

In this section, we introduce a bidding game that serves the same purpose as an efficient trading mechanism. Using terminology analogous to that introduced in Section 3, given a dissolvable partnership, one could use an efficient trading mechanism or an efficient bidding game to dissolve it. This is a useful complement to the revelation-game analysis of Section 2, because it uses strategy spaces familiar in practice, namely bids rather than valuations. In a general bidding game, the $n$ players submit sealed bids, the good is transferred to the highest bidder, and each bidder $i$ pays a total price $P_i(b_1, \ldots, b_n)$. In the efficient bidding game analyzed below, the total price $P_i$ is the sum of a price

$$p_i(b_1, \ldots, b_n) = b_i - \frac{1}{n-1} \sum_{j \neq i} b_j$$

and a side-payment $c_i$ that can precede the bidding. Note that in the efficient bidding game the winning bidder pays a positive price $p_i$, as usual, but so may the second and other high bidders. As in a standard auction, a higher bid buys the player a larger probability of winning. Here, however, making a higher bid is like buying more lottery tickets in that the purchase price of losing tickets is not refunded.

THEOREM 2: *A bidding game with prices*

$$\text{(P)} \qquad p_i(b_1, \ldots, b_n) = b_i - \frac{1}{n-1} \sum_{j \neq i} b_j,$$

*preceded by side-payments*

$$\text{(C)} \qquad c_i(r_1, \ldots, r_n) = \int_{\underline{v}}^{v_i^*} u \, dG(u) - \frac{1}{n} \sum_{j=1}^{n} \int_{\underline{v}}^{v_j^*} u \, dG(u),$$

*is an efficient bidding game: it dissolves any dissolvable partnership.*

PROOF: We solve for a strictly increasing symmetric Bayesian equilibrium. If the $n-1$ others use the strategy $b(\cdot)$, then $i$'s expected utility from bidding $b_i$ with valuation $v_i$ is

$$U_i(v_i, b_i) = \int_{\underline{v}}^{b^{-1}(b_i)} \left[ v_i - b_i + \frac{1}{n-1} b(u) + \frac{n-2}{n-1} \bar{b}(u) \right] dG(u) + \int_{b^{-1}(b_i)}^{\bar{v}} \left[ -b_i + \frac{1}{n-1} b(u) + \frac{n-2}{n-1} \bar{b}(u) \right] dG(u),$$

where $\bar{b}(u) = \int_{\underline{v}}^{u} b(v_j) \, dF(v_j \mid u)$ and $F(v_j \mid u) = F(v_j)/F(u)$. (Since types are independent, all but the highest of the $n-1$ other bids generate the same expected value, conditional on the value of the highest bid; this is $\bar{b}(u)$.) The best response for $i$ therefore solves

$$\frac{\partial U_i}{\partial b_i} = -1 + \frac{db^{-1}}{db_i} v_i g[b^{-1}(b_i)] = 0.$$

Since $\partial U_i/\partial b_i$ is positive (negative) for $b_i$ less than (greater than) $b(v_i)$, the second-order condition is satisfied. We are interested in the symmetric solution, which satisfies

$$b(v_i)=\int_{u=\underline{v}}^{v_i} u\,dG(u)+b(\underline{v}).$$

Since $b'>0$, this equilibrium is ex post efficient: the trader with the highest valuation receives the good. The constant $b(\underline{v})$ is arbitrary (it equals the lowest amount, presumably zero, that the rules of the game allow a player with valuation $\underline{v}$ to bid), and disappears when $p_i$ and $b$ are composed:

$$\text{(T)}\qquad p_i[b(v_1),\dots,b(v_n)]=-\int_{\underline{v}}^{v_i} u\,dG(u)+\frac{1}{n-1}\sum_{j\neq i}\int_{\underline{v}}^{v_j} u\,dG(u).$$

Some simple algebra verifies that (T) and (C) define the transfer rule used in the "if" part of the proof of Lemma 4, so individual rationality is guaranteed.

*Q.E.D.*

Since the side-payments depend on $r=\{r_1,\dots,r_n\}$ (through $v^*=\{v_1^*,\dots,v_n^*\}$) and $F$, but not on $v=\{v_1,\dots,v_n\}$, they can precede the bidding procedure. Their purpose is to compensate large shareholders, who are effectively dispossessed in the bidding game that follows, since the prices $p_i$ are independent of $r$ and so treat all shareholders alike. Accordingly, the side-payments are zero for the equal-shares partnership $(1/n,\dots,1/n)$.

## 5. CHARACTERIZATION RESULTS

We now offer four propositions that characterize the set of partnerships which can be dissolved efficiently. The proofs are not of interest in themselves, and so are given in the Appendix. First, we formalize the idea that it is large shareholders that make interim individual rationality difficult to achieve: for any distribution $F$, the equal-share partnership is dissolvable but the partnership in which one player owns the entire asset is not.

PROPOSITION 1: *The set of partnerships that can be dissolved efficiently is a nonempty, convex, symmetric subset of the $n-1$ dimensional simplex and is centered around the equal-shares partnership* $(1/n,\dots,1/n)$.

PROPOSITION 2: *A one-owner partnership* $\{r_1=1, r_2=0,\dots,r_n=0\}$ *cannot be dissolved efficiently.*

Proposition 2 generalizes to many buyers Myerson and Satterthwaite's (1983) result that a buyer-seller relationship cannot simultaneously satisfy ex post efficiency and interim individual rationality. This speaks to the time-honored tradition of solving complex allocation problems by resorting to lotteries: *even if* the winner is allowed to resell the object, such a scheme is inefficient because the one-owner partnership that results from the lottery cannot be dissolved efficiently.

These propositions are derived by making the appropriate substitutions into (D) of Theorem 1. Note that each partner's ownership share $r_i$ enters the inequality through $v_i^*$.

As an example, if the traders' valuations are drawn from a uniform distribution on [0, 1], then (D) simplifies to

$$(\mathrm{D}') \qquad \sum_{i=1}^{n} r_i^{n/n-1} \leq \frac{n}{n+1}.$$

Thus, for a uniform distribution, a partnership $r$ can be dissolved efficiently if and only if (D′) is satisfied. By Proposition 1, (D′) determines a convex, symmetric subset of the simplex, shown as the unshaded region in Figure 1 for the case $n = 3$. Only partnerships in the extremities of the simplex cannot be dissolved efficiently. For the uniform case, as the number of partners ($n$) grows, the percentage of partnerships that are dissolvable increases from 58% to 93% to 99% as $n$ increases from 2 to 4 to 6. Also, the percentage share of the largest possible owner in a dissolvable partnership increases from 79% to 82% to 88% as $n$ increases from 2 to 20 to 200.

By contrast with Proposition 2, however, partnerships with an arbitrarily small amount of distributed ownership *may* be dissolvable. (Note that the proof employs a very special distribution.)

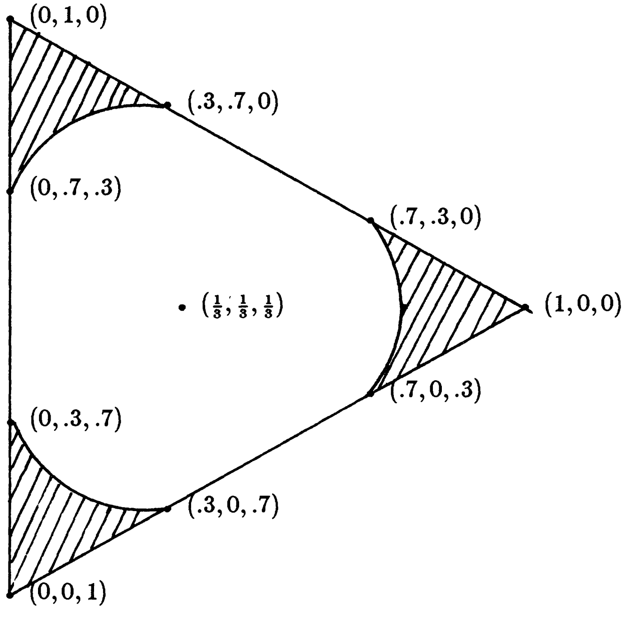


FIGURE 1—Dissolvable partnerships with $n = 3$ and $F(u) = u$.

PROPOSITION 3: *Any partnership not owned by a single player can be dissolved efficiently for some distributions F.*

Finally, if any partnership is replicated a sufficient number of times then it can be dissolved efficiently. Consider the partnership

$$R(n\,|\,m)=\{r_i=1/m,\ i=1,\ldots,m;\ r_j=0, j=m+1,\ldots,nm\}.$$

This partnership results from replicating the $n$-player, one-owner partnership $m$ times—the $m$ partners who own positive shares each own $1/m$ of the total endowment of $m$ goods, so partnerships continue to be represented by points in a simplex. The $m$-fold replication of any other $n$-player partnership can be represented in a similar way.

PROPOSITION 4: *Given F and an n-player partnership* $\{r_1,\ldots,r_n\}$, *there exists a finite M such that for all* $m>M$ *the m-fold replication of the n-player partnership can be dissolved efficiently.*

We think of this result as complementing the core-convergence theorems for exchange economies: replicating the economy sufficiently often reduces the effect of the incomplete information to zero.

An interesting special case is $R(2\,|\,m)$. For $m=1$, Myerson and Satterthwaite's result (and our Proposition 2 above) proves that the partnership cannot be dissolved efficiently. For larger values of $m$, $R$ is much like the double auction studied by Wilson (1985) and Gresik and Satterthwaite (1985) although there each bidder wants only one unit of the good, whereas here each bidder may demand up to $m$ units of the good. (Think of each $1/m$ share of the partnership as one unit of the good.) When each bidder wants one unit, Gresik and Satterthwaite show that ex post efficiency is approached in the limit; more specifically, for the uniform case, they find that 99.31 per cent of the gains from trade are realized if there are six traders on each side of the market. When each bidder wants $m$ units, on the other hand, ex post efficiency is achieved for the same example when there are as few as two traders on each side of the market. (To see this, check that (D′) holds for $R(2\,|\,2)$ for this example.)

## 6. SIMPLE TRADING RULES

The efficient bidding game proposed in Theorem 2 dissolves any dissolvable partnership. Although the efficient trading mechanism implicit in Lemma 4 and Theorem 1 achieves the same effect, we prefer the bidding game for two (somewhat imprecise) reasons. First, as mentioned above, it uses strategy spaces familiar in practice. And second, and probably more important, in the bidding game a great deal of the computational burden has been shifted from the mechanism designer to the players: the designer makes a simple calculation of side-payments and prices, using (C) and (P), while the players do most of the work in their calculation of the optimal bidding strategy $b(v_i)$. In the trading mechanism, on the other hand, the players simply report their valuations while the designer shoulders all of the computational burden.

In this spirit, we find it disappointing that the side-payments given by (C) in Theorem 2 depend on the distribution $F$, for it seems plausible that the designer will know $F$ less well than do the players. Ideally we would like a bidding game that can be described independently of $F$, so that the designer could always recommend it without assessing the distribution of the partners' private valuations. Unfortunately, the Revelation Principle is no help here: it analyzes the composition of the players' strategies and the designer's game rules, but gives no guidance as to how to decompose this map from types to outcomes into strategies for the players that may depend on $F$ and game rules for the designer that are independent of $F$.

We have not addressed the issue of finding the optimal bidding game or trading mechanism that is independent of $F$, in part because of the difficulty in formalizing this notion. (Asking only for independence of $F$, for instance, is not enough, because the designer can ask the players to report $F$, and then implement the side-payments given by (C) if the reports agree, and forbid trade if the reports do not agree.) Instead, we offer two speculative approaches to bidding games that are independent of $F$, in the hope that these ideas will be expanded upon.

First, it may be possible for the designer to use the players' bids to estimate $F$, and then to use this estimate to construct side-payments that relax the individual rationality constraints, like those in (C). This process seems both complex and delicate.[4]

Second, some bidding games that are independent of $F$ can dissolve a limited subset of the set of dissolvable partnerships. In particular, the game we discuss below dissolves the equal-shares partnership for any distribution $F$. In addition, this bidding game has three other virtues when compared to the efficient bidding game in Theorem 2. First, it is simple and familiar. Second, it is less vulnerable to collusion. (In the efficient bidding game, a cartel saves the cost of all losing bids by submitting only one nonzero bid.) And third, it relies less heavily on the risk neutrality of the bidders, since only the winner is required to pay.

Specifically, we consider a "$k+1$-price auction" in which the players submit sealed bids and the good is transferred to the highest bidder, who pays each of the others

$$p(b_1, b_2, \ldots, b_n) = \frac{1}{n}[kb_s + (1-k)b_f],$$

---

[4] More precisely, estimating $F$ seems complex and using the estimate seems delicate. As an example, suppose that $F$ is known to be approximately uniform on $[0, \bar{v}]$ with $\bar{v} \in [\underline{v}, \bar{V}]$. Consider playing the bidding game of Theorem 2 *without* the side-payments. Then for every pair of players $\{i, j\}$, use the remaining $n-2$ players' bids to estimate $F$, as follows. First, use the symmetric equilibrium bidding strategy identified in the text to map an arbitrary distribution of valuations $F$ into a distribution of bids. And second, vary $F$ over the set of distributions described above in order to maximize some goodness-of-fit criterion imposed on the two distributions of bids, one observed, and the other calculated. Now use this estimate to calculate the side-payment $c_j(r_1, \ldots, r_n)$ given in (C) and let $i$ pay $j$ the amount $c_j/(n-1)$. In this construction, the payments received by any one player depend only on the other players' bids, so the equilibrium strategies are unaffected. Therefore, the size of the subset of the set of dissolvable partnerships that can be dissolved in this way depends only on how well these elaborately constructed side-payments mimic those defined by (C) when $F$ is known.

where $b_f$ and $b_s$ are the first- and second-highest bids from $\{b_1, b_2, \ldots, b_n\}$, and $k \in [0, 1]$. For $k = 0$ this is like a first-price auction, for $k = 1$ it is like a second-price auction, and for $k = \frac{1}{2}$ it is the split-the-difference scheme described by Samuelson (1985).

Note that the revenue from bidding (namely, the highest bidder's bid) is divided equally among all the bidders. This is important. When the original ownership shares are unequal, the individual rationality constraints could be more easily met by paying losing bidders in proportion to their shares, but then partners owning different shares would have different equilibrium bidding strategies so the partner with the highest valuation might not win, violating ex post efficiency.[5]

We begin by calculating an equilibrium bidding strategy for this auction. Calculating the interim expected utility associated with this equilibrium then determines the set of partnerships that can be dissolved efficiently using the $k+1$-price auction. (Again, the terminology is analogous to that introduced in Section 3.)

PROPOSITION 5: *A $k+1$-price auction has a symmetric equilibrium bidding strategy given by*

$$b(v_i) = v_i - \frac{\int_{z=F^{-1}(k)}^{v_i} [F(z) - k]^n \, dz}{[F(v_i) - k]^n}.$$

PROPOSITION 6: *The set of partnerships that can be dissolved efficiently using a $k+1$ price auction is a nonempty, convex, symmetric subset of the simplex and is centered around the equal-shares partnership* $(1/n, \ldots, 1/n)$.

Thus, an equal-shares partnership can always be dissolved efficiently by any $k+1$-price auction. Such a simple auction only works, however, when partners' shares are approximately equal, since the auction ignores the ownership rights $r$ and this makes large shareholders unwilling to participate. For the uniform case, the $k+1$-price auction dissolves a partnership if and only if $(\max r_i)^{n/n-1} \leq 1/(n-1)$, which for $n = 2$, $n = 20$, and $n = 200$ is satisfied if no partner's share exceeds 57.7%, 5.54% and 0.511%, respectively. (A special property of the uniform distribution is that these results are independent of $k$. Contrast these results, however, with the corresponding results for the efficient bidding game, which are given after Proposition 2.) The intuition is that, because the auction treats all players as if they owned share $1/n$, large shareholders will participate only if the expected gain from trade exceeds the cost of being, in effect, dispossessed. As $n$ increases, the expected gain from trade of the worst-off type decreases: a player with high share and high valuation becomes almost certain to be just outbid by players with slightly higher valuations. Thus given a share $\rho \in [0, 1]$ there will exist some $N_\rho$ such that a partner with share $\rho$ will be willing to participate only if $n \leq N_\rho$, and in the limit, only shareholders with $\rho \leq 1/n$ are willing to participate.

---

[5] We could for every partner $j$ divide $j$'s bid among the other $(n-1)$ players in proportion to the other's relative shares, since then incentives for the bidders are unaffected by their relative shares. This is an example of the type of auction discussed in the previous footnote and would typically perform better than the auction considered here, at some cost in terms of greater complexity.

PROPOSITION 7: *As $n \to \infty$, the only partnership that can be dissolved efficiently by a $k+1$-price auction is the equal-shares partnership $(1/n, \ldots, 1/n)$. That is, letting $\rho_n$ be the largest share in a n-player partnership that any partner can have such that the partnership can be dissolved efficiently, $\rho_n/(1/n) \to 1$ as $n \to \infty$.*

## 7. CONCLUSION

A simple extension of Myerson and Satterthwaite (1983) shows that with incomplete information no mechanism can guarantee that an object to be traded will be allocated to the person who values it most, if the object is initially owned by a single party. In contrast, we show that if the ownership is distributed among a partnership, ex-post efficient allocation is often possible. Further, when it is possible, it can be achieved by a simple bidding game. In a more general model of partnerships, our observation that the range of partnerships that can be dissolved efficiently is centered around equal shares suggests that this might be a factor influencing the way in which partnerships are formed.

*Yale School of Management, Box 1A, Yale Station, New Haven, CT 06520, U.S.A.,*
*Dept. of Economics, Massachusetts Institute of Technology, Cambridge, MA 02139, U.S.A.,*
*St. Catherines College and The Institute of Economics and Statistics, Oxford University, U.K.*

*Manuscript received October, 1984; final revision received July, 1986.*

## APPENDIX

This Appendix supplies the proofs of Lemmas 1-4 and Propositions 1-7.

LEMMA 1: *The trading mechanism $\langle s, t\rangle$ is incentive compatible if and only if for every $i \in N$, $S_i$ is increasing and*

$$\text{(IC)} \qquad T_i(v_i^*) - T_i(v_i) = \int_{v_i^*}^{v_i} u\, dS_i(u)$$

*for all $v_i, v_i^* \in [\underline{v}, \bar{v}]$.*

PROOF: *Only If.* If $\langle s, t\rangle$ is incentive compatible, then $U_i(v_i) = v_i S_i(v_i) + T_i(v_i) \geq v_i S_i(u) + T_i(u)$, or equivalently

$$U_i(v_i) \geq U_i(u) + (v_i - u) S_i(u),$$

implying that $U_i$ has a supporting hyperplane at $u$ with slope $S_i(u) \geq 0$. Thus, $U_i$ is convex and has derivative $dU_i/dv_i = S_i$ almost everywhere. Also, $S_i$ must be increasing, and

$$U_i(v_i) - U_i(v_i^*) = \int_{v_i^*}^{v_i} S_i(u)\, du.$$

(We use the Stieltjes integral throughout this paper, so that any discontinuities in the expected share function are accounted for in the integral.) By integration by parts,

$$\int_{v_i^*}^{v_i} S_i(u)\,du = v_i S_i(v_i) - v_i^* S_i(v_i^*) - \int_{v_i^*}^{v_i} u\,dS_i(u),$$

which together with the definition of $U_i$ yields (IC).

*If.* Adding the identity

$$v_i[S_i(v_i) - S_i(v_i^*)] = v_i \int_{v_i^*}^{v_i} dS_i(u)$$

to (IC) results in

$$v_i[S_i(v_i) - S_i(v_i^*)] + T_i(v_i) - T_i(v_i^*) = \int_{v_i^*}^{v_i} (v_i - u)\,dS_i(u) \geqslant 0,$$

where the inequality follows because the integrand is nonnegative for all $v_i, u \in [\underline{v}, \bar{v}]$, since $S_i$ is increasing. Rearranging the terms on the left-hand side yields

$$v_i S_i(v_i) + T_i(v_i) \geqslant v_i S_i(v_i^*) + T_i(v_i^*),$$

which is incentive compatibility. *Q.E.D.*

LEMMA 2: *Given an incentive-compatible mechanism $\langle s, t\rangle$, trader i's net utility is minimized at* $v_i^* = \frac{1}{2}[\inf(V_i^*) + \sup(V_i^*)] \in [\underline{v}, \bar{v}]$, *where*

$$V_i^* = \{v_i \mid S_i(u) < r_i\ \forall\ u < v_i;\ S_i(w) > r_i\ \forall\ w > v_i\}.$$

PROOF: The net utility to trader $i$ with valuation $v_i$ is $U_i(v_i) - r_i v_i$, which is convex in $v_i$ by Lemma 1. Therefore, trader $i$'s net utility is minimized at the point where the left and right derivatives of $U_i$ with respect to $v_i$ bound $r_i$. But $dU_i/dv_i = S_i$ almost everywhere, $S_i$ is increasing, and $T_i$ is decreasing in $v_i$. Four cases need to be considered. First, suppose that $S_i(u) > r_i$ or $S_i(u) < r_i$ for all $u \in [\underline{v}, \bar{v}]$; then the minimum occurs at the boundaries $v_i^* = \underline{v}$ or $v_i^* = \bar{v}$, respectively. The next three cases deal with the case where there exists $u$ and $w$ such that $S_i(u) > r_i$ and $S_i(w) < r_i$. (1) Suppose $S_i$ is continuous and strictly increasing; then there exists a unique $v_i^*$ such that $S_i(v_i^*) = r_i$, which minimizes trader $i$'s net utility. (2) If $S_i$ is not continuous and $S_i$ jumps past $r_i$, then the $v_i$ at which $S_i$ jumps minimizes net utility. (3) Finally, if $S_i(u) = r_i$ over an interval, then each type in the interval is equally worse off and we can arbitrarily select any valuation in the interval to be the worst-off type. *Q.E.D.*

LEMMA 3: *An incentive-compatible mechanism $\langle s, t\rangle$ is individually rational if and only if for all $i \in N$*

$$\text{(IR)} \qquad T_i(v_i^*) \geqslant 0,$$

*where $v_i^*$ is defined in Lemma 2.*

PROOF: We need only check individual rationality at the valuation $v_i^*$ defined in Lemma 2. Thus, the individual-rationality constraint becomes $v_i^* S_i(v_i^*) + T_i(v_i^*) \geqslant r_i v_i^*$, or $r_i v_i^* + T_i(v_i^*) \geqslant r_i v_i^*$. *Q.E.D.*

LEMMA 4: *For any share function s such that $S_i$ is increasing for all $i \in N$, there exists a transfer function t such that $\langle s, t\rangle$ is incentive compatible and individually rational if and only if*

$$\text{(I)} \qquad \sum_{i=1}^{n} \left[\int_{v_i^*}^{\bar{v}} [1 - F(u)]u\,dS_i(u) - \int_{\underline{v}}^{v_i^*} F(u)u\,dS_i(u)\right] \geqslant 0,$$

*where $v_i^*$ is defined in Lemma 2.*

PROOF: *Only if.* Suppose $\langle s, t\rangle$ is incentive compatible and individually rational. Then from Lemma 1,

$$T_i(v_i) = T_i(v_i^*) - \int_{v_i^*}^{v_i} u\,dS_i(u).$$

Integrating over all types in $[\underline{v}, \bar{v}]$ yields

$$\begin{aligned}\mathscr{E}_i\{T_i(v_i)\} &= T_i(v_i^*) - \int_{v_i=\underline{v}}^{\bar{u}} \int_{u=v_i^*}^{v_i} u \, dS_i(u) \, dF(v_i) \\ &= T_i(v_i^*) - \int_{u=v_i^*}^{\bar{v}} \int_{v_i=u}^{\bar{u}} dF(v_i) u \, dS_i(u) + \int_{u=\underline{v}}^{v_i^*} \int_{v_i=\underline{v}}^{u} dF(v_i) u \, dS_i(u) \\ &= T_i(v_i^*) - \int_{v_i^*}^{\bar{v}} [1-F(u)] u \, dS_i(u) + \int_{\underline{v}}^{v_i^*} F(u) u \, dS_i(u),\end{aligned}$$

where the second line follows from changing the order of integration. Budget balance requires $\sum_{i=1}^n t_i(v) = 0$ for all $v$, so we have

$$\sum_{i=1}^n \mathscr{E}_i\{T_i(v_i)\} = \mathscr{E}_N\left\{\sum_{i=1}^n t_i(v)\right\} = 0.$$

Therefore, summing over all traders yields

$$\sum_{i=1}^n T_i(v_i^*) = \sum_{i=1}^n \left[\int_{v_i^*}^{\bar{v}} [1-F(u)] u \, dS_i(u) - \int_{\underline{v}}^{v_i^*} F(u) u \, dS_i(u)\right].$$

From Lemma 3, $T_i(v_i^*)$ must be nonnegative for all $i$, which implies $\sum_{i=1}^n T_i(v_i^*) \geq 0$.

*If.* The proof is by construction. Let

$$t_i(v) = c_i - \int_{\underline{v}}^{v_i} u \, dS_i(u) + \frac{1}{n-1} \sum_{j \neq i} \int_{\underline{v}}^{v_j} u \, dS_j(u),$$

where $\sum_{i=1}^n t_i(v) = 0$ implies $\sum_{i=1}^n c_i = 0$. Then, after changing the order of integration,

$$T_i(v_i) = c_i - \int_{\underline{v}}^{v_i} u \, dS_i(u) + \frac{1}{n-1} \sum_{j \neq i} \int_{\underline{v}}^{\bar{v}} [1-F(u)] u \, dS_j(u),$$

so Lemma 1 guarantees that $\langle s, t\rangle$ is incentive compatible. Finally, by Lemma 3, we have individual rationality if and only if $T_i(v_i^*) \geq 0$. A little algebra shows the hypothesis of Lemma 4 to be equivalent to the condition $\sum_{i=1}^n T_i(v_i^*) \geq 0$, so we can choose

$$c_i = \frac{1}{n} \sum_{i=1}^n T_i(v_i^*) + \int_{\underline{v}}^{v_i^*} u \, dS_i(u) - \frac{1}{n-1} \sum_{j \neq i} \int_{\underline{v}}^{\bar{v}} [1-F(u)] u \, dS_j(u),$$

which results in $T_i(v_i^*) = (1/n) \sum_{i=1}^n T_i(v_i^*) \geq 0$. *Q.E.D.*

PROPOSITION 1: *The set of partnerships that can be dissolved efficiently is a nonempty, convex, symmetric subset of the $n-1$-dimensional simplex and is centered around the equal shares partnership* $(1/n, \ldots, 1/n)$.

PROOF: Use (D) to define $\phi : \mathscr{R}^n \to \mathscr{R}$ by

$$\phi(r) = \sum_{i=1}^n \left[\int_{v_i^*}^{\bar{v}} v_i f(v_i) F(v_i)^{n-2} \, dv_i - \int_{\underline{v}}^{\bar{v}} v_i f(v_i) F(v_i)^{n-1} \, dv_i\right].$$

Convexity follows from concavity of $\phi$, which we have because

$$\frac{\partial \phi}{\partial r_i} = \frac{-v_i^* dF(v_i^*)^{n-1}}{n-1} \cdot \frac{dv_i^*}{dr_i} = \frac{-v_i^*}{n-1},$$

$$\frac{\partial^2 \phi}{\partial r_i \, \partial r_j} = 0, \quad \text{and} \quad \frac{\partial^2 \phi}{\partial r_i^2} = -\frac{1}{n-1} \cdot \frac{dv_i^*}{dr_i} < 0.$$

Symmetry follows from relabeling the partners. Finally, $\phi(1/n, \ldots, 1/n) > 0$ because at $v_i^*(1/n) = F^{-1}(1/n^{1/n-1})$ we have

$$\begin{aligned}&\int_{v_i^*}^{\bar{v}} v_i f(v_i) F(v_i)^{n-2} \, dv_i - \int_{\underline{v}}^{\bar{v}} v_i f(v_i) F(v_i)^{n-1} \, dv_i \\ &\quad = \frac{\bar{v} - v_i^*}{n(n-1)} + \frac{1}{n} \int_{\underline{v}}^{v_i^*} F(v_i))^n \, dv_i - \int_{v_i^*}^{\bar{v}} \left[\frac{nF(v_i)^{n-1} - (n-1)F(v_i)^n}{n(n-1)}\right] dv_i > 0,\end{aligned}$$

where the equality arises after integrating each term by parts, and the inequality holds since $nF^{n-1}-(n-1)F^n \leqslant 1$ for all $v_i \in [v_i^*, \underline{v}]$, so the first term dominates the third. *Q.E.D.*

PROPOSITION 2: *A one-owner partnership* $\{r_1=1, r_2=0, \ldots, r_n=0\}$ *cannot be dissolved efficiently.*

PROOF: For the $n$-player partnership $\{r_1=1, r_2=0, \ldots, r_n=0\}$, integrating by parts in (D) yields

$$-\int_{\underline{v}}^{\bar{v}} F^{n-1}\,dv+\int_{\underline{v}}^{\bar{v}} F^n\,dv \geqslant 0,$$

which fails for all finite $n$. *Q.E.D.*

PROPOSITION 3: *Any partnership not owned by a single player can be dissolved efficiently for some distributions $F$.*

PROOF: The proof is by construction, using the distribution $F(u)=\{1-[u(v)]^{-\alpha}\}/\{1-T^{-\alpha}\}$ where $\alpha \in (0, \frac{1}{2})$ and $u(v)=1+\{(T-1)(v-\underline{v})/(\bar{v}-\underline{v})\}$ (so $u(\underline{v})=1$ and $u(\bar{v})=T$). Take an arbitrary partnership $\{r \mid r_i<1\ \forall\ i\}$ and let $d=1-T^{-\alpha}$. Using a binomial expansion for $F^{n-2}$ and $F^{n-1}$ and performing the integration indicated in (D) yields

$$\begin{aligned}\phi(r)=\Bigg\{\sum_{i=1}^{n}\frac{\alpha}{d^{n-1}}\left[\frac{u^{1-\alpha}}{1-\alpha}-(n-2)\frac{u^{1-2\alpha}}{1-2\alpha}+\cdots\right]\Bigg|_{u=u(v_i^*(r_i))}^{T}\\ -n\frac{\alpha}{d^n}\left[\frac{u^{1-\alpha}}{1-\alpha}-(n-1)\frac{u^{1-2\alpha}}{1-2\alpha}+\cdots\right]\Bigg|_{u=1}^{T}\left(\frac{\bar{v}-\underline{v}}{T-1}\right).\end{aligned}$$

It suffices to show that the above terms in $T$ in the braces tend to $+\infty$ with $T$, because the terms in $T$ ignored are of lower order, and so are insignificant, and all the terms in the lower limits are finite because $u(v_i^*(r_i))$ approaches a finite limit, $\forall\ r_i<1$. (It is crucial that we have $r_i<1$, since $u(v_i^*(1))=T$, which does not stay finite as $T\to\infty$.) To show that the terms in $T$ approach $\infty$, replace $T$ by $(1-d)^{-1/\alpha}$ and collect terms. This yields

$$\frac{n\alpha}{d^{n-1}}\left((1-d)^{2-1/\alpha}\left[\frac{1}{1-2\alpha}-\frac{1}{d(1-\alpha)}\right]+\frac{(n-1)(1-d)^{3-1/\alpha}}{d(1-2\alpha)}\right).$$

As $T\to\infty$, $d\to 1$. Therefore, the second term above can be ignored, since it has an extra factor of $(1-d)$. Since $\alpha\in(0,\frac{1}{2})$, $2-1/\alpha<0$, so the first term goes to $\infty$ as $d\to 1$ provided

$$\frac{1}{1-2\alpha}-\frac{1}{d(1-\alpha)}>0,$$

which holds for $d\in((1-2\alpha)/(1-\alpha), 1)$. So $\phi(r)>0$ for sufficiently large $T$. *Q.E.D.*

PROPOSITION 4: *Given $F$ and an $n$-player partnership $\{r_1, \ldots, r_n\}$, there exists a finite $M$ such that for all $m>M$ the $m$-fold replication of the $n$-player partnership can be dissolved efficiently.*

PROOF: By the concavity of $\phi$ established in Proposition 1, it suffices to show that the result holds for the $n$-player partnership $\{r_1=1, r_2=0, \ldots, r_n=0\}$, the $m$-fold replication of which is $\{r_i=1/m, i=1, \ldots, m;\ r_j=0, j=m+1, \ldots, mn\}$. Let $mn=N$. Then $m=N/n$ and the partnership of interest is $\{r_i=n/N,\ i=1, \ldots, N/n;\ r_j=0, j=(N/n)+1, \ldots, N\}$. After integrating by parts in (D) and collecting terms, we have

$$\begin{aligned}\frac{1}{N}\phi(R)=\left[\frac{\bar{v}-v_i^*}{N(N-1)}-\int_{v_i^*}^{\bar{v}}\left(\frac{NF^{N-1}-(N-1)F^N}{N(N-1)}\right)du\right]\\ +\left[\frac{1}{n}\int_{\underline{v}}^{v_i^*}\frac{F^{N-1}}{N-1}\,du-\int_{\underline{v}}^{v_i^*}\left(\frac{NF^{N-1}-(N-1)F^N}{N(N-1)}\right)du\right],\end{aligned}$$

where $v_i^*=v_i^*(n/N)=F^{-1}[(n/N)^{1/N-1}]$. Since $NF^{N-1}-(N-1)F^N\leqslant 1$ over $[v_i^*, \bar{v}]$, the first pair of terms is strictly positive. The second pair is positive for sufficiently large $N$ if

$$\lim_{N\to\infty}\frac{(N-1)\int_{\underline{v}}^{v_i^*}F^N\,du}{N\int_{\underline{v}}^{v_i^*}F^{N-1}\,du}>1-\frac{1}{n}.$$

Consider two arbitrary values $k_1 < k_2$ from $(\underline{v}, \bar{v})$, and let $K_i = F(k_i)$ for $i = 1, 2$. As $N \to \infty$, $v_i^* \to \bar{v}$, so for sufficiently large $N$ we have $k_1 < k_2 < v_i^*$. Let $I = \int_{k_1}^{k_2} F^N \, du$ and $J = \int_{k_2}^{v_i^*} F^N \, du$. Then $\int_{k_1}^{k_2} F^{N-1} \, du < I/K_1$ and $\int_{k_2}^{v_i^*} F^{N-1} \, du < J/K_2 < J/K_1$. So

$$\frac{\int_{\underline{v}}^{v_i^*} F^N \, du}{\int_{\underline{v}}^{v_i^*} F^{N-1} \, du} > \frac{\int_{k_1}^{k_2} F^N \, du + \int_{k_2}^{v_i^*} F^N \, du}{(k_1 - \underline{v}) K_1^{N-1} + \int_{k_1}^{k_2} F^{N-1} \, du + \int_{k_2}^{v_i^*} F^{N-1} \, du}$$

$$> K_1 \frac{I + J}{(k_1 - \underline{v}) K_1^N + I + J}.$$

Since $I + J > J > (v_i^* - k_2) K_2^N$, we have

$$K_1 \frac{I + J}{(k_1 - \underline{v}) K_1^N + I + J} > K_1 \frac{(v_i^* - k_2) K_2^N}{(k_1 - \underline{v}) K_1^N + (v_i^* - k_2) K_2^N}$$

$$= K_1 \frac{v_i^* - k_2}{(k_1 - \underline{v})(K_1/K_2)^N + (v_i^* - k_2)}.$$

Fix $\varepsilon > 0$, and let $K_1 = 1 - \frac{1}{2}\varepsilon$, and $K_2 = 1 - \frac{1}{4}\varepsilon$. Then $(K_1/K_2)^N \to 0$ while $v_i^* - k_2 \to \bar{v} - k_2$, so the last ratio above approaches $1 - \frac{1}{2}\varepsilon$, and can therefore be made to exceed $1 - (1/n)$ for fixed $n$, as required.

*Q.E.D.*

PROPOSITION 5: *A $k+1$-price auction has a symmetric equilibrium bidding strategy given by*

$$b(v_i) = v_i - \frac{\int_{z=F^{-1}(k)}^{v_i} [F(z) - k]^n \, dz}{[F(v_i) - k]^n}.$$

PROOF: Let $G(x) = F(x)^{n-1}$. If $i$ conjectures that the $n-1$ others will use the strategy $b(v_j)$, then $i$'s expected utility from bidding $b_i$ with valuation $v_i$ is

$$U_i(v_i, b_i) = \int_{\underline{v}}^{b^{-1}(b_i)} \left( v_i - \frac{n-1}{n}[kb(x) + (1-k)b_i] \right) dG(x)$$

$$+ \int_{x=b^{-1}(b_i)}^{\bar{v}} \int_{y=\underline{v}}^{b^{-1}(b_i)} \frac{1}{n}[kb_i + (1-k)b(x)] \, dH(y|x) \, dG(x)$$

$$+ \int_{x=b^{-1}(b_i)}^{\bar{v}} \int_{y=b^{-1}(b_i)}^{x} \frac{1}{n}[kb(y) + (1-k)b(x)] \, dH(y|x) \, dG(x),$$

where $H(y|x) = [F(y)/F(x)]^{n-2}$ (for $y \leqslant x$) is the distribution of the second-largest of the $n-1$ other bids given that the largest is $x$. The best response for $i$ therefore solves

$$\frac{\partial U_i}{\partial b_i} = (v_i - b_i) g[b^{-1}(b_i)] \frac{db^{-1}}{db_i} - \frac{n-1}{n} F[b^{-1}(b_i)]^{n-2} (F[b^{-1}(b_i)] - k) = 0.$$

The symmetric equilibrium $b(v_i)$ satisfies

$$v_i - b(v_i) = \frac{1}{n} b'(v_i) \frac{F(v_i) - k}{f(v_i)}.$$

This linear differential equation can be solved using the integrating factor $[F(v_i) - k]^n$; the solution is a one-parameter family satisfying

$$[v_i - b(v_i)][F(v_i) - k]^n = \int_c^{v_i} [F(u) - k]^n \, du.$$

We choose $c$ to make the right-hand side equal to zero at $v_i = F^{-1}(k)$; otherwise, bids tend to $\pm\infty$ as $v_i$ approaches $F^{-1}(k)$ from above or below. This choice of $c$ yields the symmetric equilibrium

$$b(v_i) = v_i - \frac{\int_{z=F^{-1}(k)}^{v_i} [F(z) - k]^n \, dz}{[F(v_i) - k]^n},$$

and truth-telling occurs at $v_i = F^{-1}(k)$. Finally, since $b' > 0$, this equilibrium is ex-post efficient: the partner with the highest valuation receives the good with probability one.

It remains, then, to verify interim individual rationality. That is, we want $\tilde{w}(v_i, r_i) = U[v_i, b(v_i)] - r_i v_i \geq 0$ for all $v_i \in [\underline{v}, \bar{v}]$, where $U[v_i, b(v_i)]$ is

$$\int_{\underline{v}}^{v_i}\left(v_i - \frac{n-1}{n}[kb(x)+(1-k)b(v_i)]\right) dG(x)$$

$$+\int_{x=v_i}^{\bar{v}}\int_{y=\underline{v}}^{v_i}\frac{1}{n}[kb(v_i)+(1-k)b(x)]\, dH(y|x)\, dG(x)$$

$$+\int_{x=v_i}^{\bar{v}}\int_{y=v_i}^{x}\frac{1}{n}[kb(y)+(1-k)b(x)]\, dH(y|x)\, dG(x).$$

Partially differentiating with respect to $v_i$ and applying the first-order condition shows that, for fixed $r_i$, $\tilde{w}$ is minimized at $v_i^*(r_i) = G^{-1}(r_i)$. Let $w(r_i) = \tilde{w}[v_i^*(r_i), r_i]$; then

$$\frac{n}{n-1}w(r_i) = (1-k)\left\{\frac{1}{n-1}\int_{v_i^*}^{\bar{v}} b(x)\, dG(x) - r_i b(v_i^*)\right\}$$

$$+k\left\{F(v_i^*)^{n-2}[1-F(v_i^*)]b(v_i^*) - \int_{\underline{v}}^{v_i^*} b(x)\, dG(x)\right.$$

$$\left.+\frac{1}{n-1}\int_{x=v_i^*}^{\bar{v}}\int_{y=v_i^*}^{x} b(y)\, dH(y|x)\, dG(x)\right\}. \qquad \text{Q.E.D.}$$

Proposition 6: *The set of partnerships that can be dissolved efficiently using a $k+1$-price auction is a nonempty, convex, symmetric subset of the simplex and is centered around the equal-shares partnership $(1/n, \ldots, 1/n)$.*

Proof: Convexity follows from the concavity of $w(r_i)$, which holds because $w'(r_i) = -v_i^*(r_i)$ and $w''(r_i) = -d/dr_i\, v_i^*(r_i) < 0$ since $v_i^* = F^{-1}(r_i^{1/(n-1)})$. Symmetry follows from relabeling the partners. Finally consider the equal-shares partnership in two steps. First, consider the terms involving $1-k$. We have

$$\frac{1}{n-1}\int_{v_i^*}^{\bar{v}} b(x)\, dG(x) \geq r_i b(v_i^*)$$

at $v_i^* = G^{-1}(1/n)$ by substituting $b(v_i^*)$ for $b(x)$ in the integral and simplifying. And second, consider the terms involving $k$. We have

$$F(v_i^*)^{n-2}[1-F(v_i^*)]b(v_i^*) \geq \int_{\underline{v}}^{v_i^*} b(x)\, dG(x) - \frac{1}{n-1}\int_{x=v_i^*}^{\bar{v}}\int_{y=v_i^*}^{x} b(y)\, dH(y|x)\, dG(x)$$

at $v_i^* = G^{-1}(1/n)$, again by substituting $b(v_i^*)$ for $b(x)$ and $b(y)$ in the integrals and simplifying. Q.E.D.

Proposition 7: *As $n \to \infty$, the only partnership that can be dissolved efficiently by a $k+1$-price auction is the equal-shares partnership $(1/n, \ldots, 1/n)$. That is, letting $\rho_n$ be the largest share in a n-player partnership that any partner can have such that the partnership can be dissolved efficiently, $\rho_n/(1/n) \to 1$ as $n \to \infty$.*

Proof: It suffices to show that given $\delta > 0$, there exists $N$ such that for all $n > N$, interim individual rationality fails for a player with share $(1+\delta)/n$. Let

$$d(\delta) = F\left[\bar{v}\left(\frac{1+\frac{1}{2}\delta}{1+\delta}\right)\right] < 1.$$

Interim individual rationality for a player with share $(1+\delta)/n$ and valuation $\bar{v}((1+\frac{1}{2}\delta)/(1+\delta)$ implies

$$\left[\bar{v}\left(\frac{1+\frac{1}{2}\delta}{1+\delta}\right)\right]\left[\left(\frac{1+\delta}{n}\right)\right] \leq \text{(probability of losing)(value of losing)}$$

$$+\text{(probability of winning)(value of winning)}$$

$$<(1)\left(\frac{\bar{v}}{n}\right)+(d^{n-1})(\bar{v}).$$

Thus,

$$(1+\tfrac{1}{2}\delta)<1+nd^{n-1},$$

which is necessarily false for all sufficiently large $n$. *Q.E.D.*

## REFERENCES

GRESIK, THOMAS A., AND MARK A. SATTERTHWAITE (1985): "The Rate at Which a Simple Market Becomes Efficient as the Number of Traders Increases: An Asymptotic Result for Optimal Trading Mechanisms," Working Paper No. 641, Graduate School of Management, Northwestern University.

HOLMSTROM, BENGT, AND ROGER B. MYERSON (1983): "Efficient and Durable Decision Rules with Incomplete Information," *Econometrica*, 51, 1799-1819.

MYERSON, ROGER B. (1979): "Incentive Compatibility and the Bargaining Problem," *Econometrica*, 47, 61-73.

MYERSON, ROGER B., AND MARK A. SATTERTHWAITE (1983): "Efficient Mechanisms for Bilateral Trading," *Journal of Economic Theory*, 28, 265-281.

SAMUELSON, WILLIAM (1985): "A Comment on the Coase Theorem," in *Game Theoretic Models of Bargaining*, edited by Alvin Roth. Cambridge: Cambridge University Press.

VAN DAMME, ERIC (1985): "Fair Allocation of an Indivisible Commodity," Working Paper, University of Technology, Delft, the Netherlands.

WILSON, ROBERT (1985): "Incentive Efficiency of Double Auctions," *Econometrica*, 53, 1101-1116.

# LINKED CITATIONS

*- Page 1 of 2 -*

**Dissolving a Partnership Efficiently**
Peter Cramton; Robert Gibbons; Paul Klemperer
*Econometrica*, Vol. 55, No. 3. (May, 1987), pp. 615-632.
Stable URL:
http://links.jstor.org/sici?sici=0012-9682%28198705%2955%3A3%3C615%3ADAPE%3E2.0.CO%3B2-3

---

## [Footnotes]

[3] **Efficient and Durable Decision Rules with Incomplete Information**
Bengt Holmström; Roger B. Myerson
*Econometrica*, Vol. 51, No. 6. (Nov., 1983), pp. 1799-1819.
Stable URL:
http://links.jstor.org/sici?sici=0012-9682%28198311%2951%3A6%3C1799%3AEADDRW%3E2.0.CO%3B2-H

## References

**Efficient and Durable Decision Rules with Incomplete Information**
Bengt Holmström; Roger B. Myerson
*Econometrica*, Vol. 51, No. 6. (Nov., 1983), pp. 1799-1819.
Stable URL:
http://links.jstor.org/sici?sici=0012-9682%28198311%2951%3A6%3C1799%3AEADDRW%3E2.0.CO%3B2-H

**Incentive Compatibility and the Bargaining Problem**
Roger B. Myerson
*Econometrica*, Vol. 47, No. 1. (Jan., 1979), pp. 61-73.
Stable URL:
http://links.jstor.org/sici?sici=0012-9682%28197901%2947%3A1%3C61%3AICATBP%3E2.0.CO%3B2-O

# LINKED CITATIONS

*- Page 2 of 2 -*

**Incentive Efficiency of Double Auctions**

Robert Wilson

*Econometrica*, Vol. 53, No. 5. (Sep., 1985), pp. 1101-1115.

Stable URL:

http://links.jstor.org/sici?sici=0012-9682%28198509%2953%3A5%3C1101%3AIEODA%3E2.0.CO%3B2-3

**NOTE:** *The reference numbering from the original has been maintained in this citation list.*

**EXHIBIT PC-4**

Exhibit PC-4

# Applicant Auctions for Internet Top-Level Domains: Resolving Conflicts Efficiently

Peter Cramton, University of Maryland
Ulrich Gall, Stanford University
Pacharasut Sujarittanonta, Cramton Associates LLC
Robert Wilson, Stanford University

27 January 2013 (*preliminary*)

## Abstract

The prospect of using auctions to resolve conflicts among parties competing for the same top-level internet domains is described. In the auctions investigated, the winner's payment is divided among the losers. For first-price and second-price sealed-bid auctions, we characterize equilibrium bidding strategies and provide examples, assuming bidders' valuations are distributed independently and are either symmetrically or asymmetrically distributed. The qualitative properties of equilibria reveal novel features; for example, in a second-price auction a bidder might bid more than her valuation in order to drive up the winner's payment. Even so, examples indicate that in symmetric cases a bidder's expected profit is the same in the two auction formats. We then test in the experimental lab two auction formats that extent the setting from a single domain to the actual setting with many domains. The first format is a sequential first-price sealed-bid auction; the second format is a simultaneous ascending clock auction. The framing and subjects were chosen to closely match the actual setting. Subjects were PhD students at the University of Maryland with training in game theory and auction theory. Each subject played the role of an actual company (e.g., Google) and bid for domains (e.g., *.book*) consistent with the company's applications. Subjects were given instructions explaining the auction and the equilibrium theory for the single-item case in relevant examples. Both formats achieved auction efficiencies of 98% in the lab. This high level of efficiency is especially remarkable in the case with asymmetric distributions—the format performed better than the simple single-item equilibrium despite the presence of budget constraints in the lab. This experiment together with previous results on the robustness of ascending auctions in general and simultaneous ascending clock auctions in particular suggest that the simultaneous ascending clock auction will perform best in this setting.

## 1 Introduction

The hallmark of market design is its fruitful interaction between theory and practice. This is especially true when theoretical insights guide the development of innovative market designs. A prominent instance was the development of the simultaneous ascending auction, initially for allocation of spectrum licenses and now widely used for other commodities as well. Another application will occur in 2013 when ICANN (Internet Corporation for Assigned Names and Numbers) will use a simultaneous ascending auction, called the last-resort auction, to allocate those new generic top-level domains for which the contending applicants have not reached agreements among themselves to resolve the conflict.

ICANN will retain the winning bidder's payment for each contested domain allocated via the last-resort auction. But a remarkable policy is that ICANN encourages contending applicants to resolve among themselves the competition for each domain.[1] Although competitors might negotiate a resolution of the conflict, or form a consortium to share a domain, for many domains the likely preference will be to choose one among them to be assigned the domain, using some formal process they agreed to be bound by — such as an auction among themselves. In this case the designated applicant is assigned the domain and each of the other applicants receives a refund of 70% of its application fee of $130,000.

Resolving such conflicts is akin to the well-known problem of how to dissolve a partnership efficiently (studied theoretically by Cramton, Gibbons and Klemperer, *Econometrica*, 1987), as when one partner buys the shares of the others at a price determined by an auction. In the ICANN context, however, the matter is slightly different, because rather than a partnership, the applicants (in effect) own *in common* the right to be allocated the domain. It also differs in that each applicant's outside option is, first, to refuse participation in a process to resolve the competition among themselves, and then second, to bid against the others in the subsequent ICANN last-resort auction. A third difference is that many applicants are competing for multiple domains.

The first of these three differences can be resolved only by the applicants for each domain. Here we assume they can agree to some division of the winner's payment among the losers, and we suppose for simplicity that the losers receive equal shares of the winner's payment. Such an agreement largely eliminates the second difference, because the ICANN last-resort auction is surely an inferior outside option for every applicant as compared to an auction among the applicants, for two reasons. One reason is that ICANN keeps the winner's payment in the last-resort auction, but if the applicants auction the domain among themselves then the losers divide the winner's payment among themselves, as in a knockout auction (McAfee and McMillan, *American Economic Review*, 1992). The second reason occurs most clearly in a first-price auction where the winner pays her bid, because each applicant's incentive is to bid somewhat less than she would in ICANN's auction since losing still garners a share of the winner's payment.

We show later that this particular prediction is true in a second-price or ascending auction, where the winner pays the second-highest bid, only for bidders with relatively high valuations of the domain. Thus, even applicants rather confident of winning the ICANN last-resort auction still prefer an auction among all the contending applicants in which the winner's payment is paid to the losers — and the incentive is even stronger for those likely to lose in ICANN's auction. The third difference can be handled either by

---

[1] "…, cases of contention might be resolved by community priority evaluation or an agreement among the parties. Absent that, the last-resort contention resolution mechanism will be an auction. …Applicants that are identified as being in contention are encouraged to reach a settlement or agreement among themselves that resolves the contention. …Applicants may resolve string contention in a manner whereby one or more applicants withdraw their applications." (ICANN Application Guidebook, Module 4: String Contention, pp. 4-5, 4 June 2012.)

conducting a sequence of applicant auctions for contested domains, or by a simultaneous ascending auction for many contested domains.

There are further technical considerations. For this exposition we ignore the effects of each loser's partial refund of the application fee. Moreover, we assume for simplicity that applicants' valuations of a domain are statistically independent, each drawn randomly according to a specified probability distribution that is commonly known among the applicants. In practice, of course, one expects some correlation among applicants' valuations, as when each applicant has only some estimates of factors that affect all or many of their valuations. We defer to a later exposition our analysis of the more general formulation in which it is assumed only that estimates and valuations are affiliated (i.e., non-negatively correlated everywhere) and we apply the methods of Milgrom and Weber (*Econometrica* 1982).

A primary principle of market design is to promote an efficient outcome to the extent possible. For the case addressed here with independent valuations for a single domain, this requires a design to enable the bidder who most values a domain to win it. This ensures that the gain from trade among the applicants is realized — and, of course, it is more than the ICANN last-resort auction realizes because ICANN keeps the winner's payment. Of course, perfect efficiency cannot be assured if bidders are asymmetric or some are concerned about complementarities and substitution among domains, but the success of simultaneous ascending auctions in similar contexts like spectrum auctions suggests that similarly good outcomes can be obtained for multiple domains.

As a practical matter, it is important to anticipate asymmetries among the bidders. Some of the applicants have much at stake and deep pockets (e.g., Google and Amazon are prominent applicants, and in only a few cases are they contesting the same domain, such as the domain *.talk*). Others have unique motives (e.g., the domain *.swiss* is contested by Swiss International Airlines and the Swiss Confederation, and the domain *.sas* by Scandinavian Airlines System). A single applicant (Donuts) is competing for 68% of the contested domains, and each of four others is competing for over 20% of the 232 contested domains. Thus, in using some theory to predict optimal bidding strategies and auction outcomes, it is important to allow for asymmetries among the bidders. Here we do this chiefly by supposing in the examples that some bidders are more likely than others to have higher valuations.

So, in this preliminary study we report results about equilibrium bidding strategies in sealed-bid auctions for two payment rules, the first-price rule in which the winner pays her bid, and the second-price rule in which the winner pays the second-highest bid. We characterize equilibrium bidding strategies and predicted outcomes for both asymmetric and symmetric distributions of the bidders' valuations, assuming in each case that all bidders have the same interval of possible valuations over which the probability densities of their valuations is positive. The set of bidders for each domain is known to all, since that is a feature of the ICANN situation. Thus, for each bidder the only uncertainty is about others' bids, and thus indirectly, others' valuations.

In practice, of course, one cannot expect that actual behavior conforms to predictions based on equilibrium bidding strategies, not least because the basic assumption is false that the bidders all know the probability distributions of each other's valuations. The further uncertainty about each other's beliefs will be an important factor affecting actual bidding strategies. As a first step, nevertheless, predictions about equilibrium behavior are useful because they reveal the basic motives in devising a good bidding strategy. We compare the behavior of PhD students acting as the bidders in experiments conducted in a laboratory setting with theoretical predictions.

In displaying these preliminary results, our motive is only to indicate that theoretical predictions can provide some insights into the salient features of an auction among the applicants for a single domain. We remark on these features as we proceed. Some are familiar features of first-price auctions, such as the possibility of an inefficient outcome when the bidders are asymmetric, which can occur because a bidder whose valuation is more likely to be low bids higher at each valuation than one whose valuation is likely to be high. For second-price auctions we discover that a bidder who expects to probably lose might nevertheless bid more than its valuation in an attempt to drive up the price paid by the winner. Even so, when the bidders are symmetric, the outcome is efficient in either auction format.

Before beginning the formal analysis of equilibrium bidding strategies, we recall the two payment rules. In either case the winner is the bidder offering the highest bid, and the winner's payment is distributed evenly among the losers. In a first-price auction the winner's payment is its bid, and in a second-price auction it is the second-highest bid. In what follows we first characterize bidding strategies for each payment rule when bidders are asymmetric, and provide some examples, then later provide further characterizations and illustrations when the bidders are symmetric.

## 2 Model with independent private value

Consider a sealed-bid auction of a single domain in which the winner's payment is distributed evenly among the losers. Assume that bidder $i$ has a privately known valuation $v_i$ that is independently distributed according to the probability distribution with cumulative $F_i$ and positive density $f_i$ on an interval $[0,\bar{v}]$ that is the same for all $n$ bidders. In a monotone pure-strategy equilibrium, bidder $i$ bids $\beta_i(v_i)$ if her value is $v_i$. Assume throughout that the bidding strategy $\beta_i$ is an increasing and differentiable function, and thus has an increasing and differentiable inverse function $\alpha_i$. That is, bidder $i$ bids $b$ when her valuation is $v_i = \alpha_i(b)$.

We say that two bidders have the same type if the probability distributions of their valuations are the same. Assume that there are $m_i$ bidders of the same type as bidder $i$. We characterize the equilibrium when all bidders of the same type use the same bidding strategy. For bidder $i$, therefore,

$$G_i(b) = F_i(\alpha_i(b))^{m_i-1}\prod_{j\neq i} F_j(\alpha_j(b))^{m_j}$$

is the probability that others' bids are less than $b$, and thus $i$ wins with probability $G_i(b)$ if she bids $b$. Let $g_i(b)$ be its associated density at the bid $b$, where

$$g_i(b) = F_i(\alpha_i(b))^{m_i - 1} \sum_{j \neq i} \left( \prod_{k \neq i, j} F_k(\alpha_k(b))^{m_k} \right) m_j F_j(\alpha_j(b))^{m_j - 1} f_j(\alpha_j(b)) \alpha_j'(b)$$

$$+ \left( \prod_{j \neq i} F_j(\alpha_j(b))^{m_j} \right) (m_i - 1) F_i(\alpha_i(b))^{m_i - 2} f_i(\alpha_i(b)) \alpha_i'(b).$$

## 2.1 Asymmetric bidders in a first-price auction

In a first-price auction, from the perspective of any one bidder with value $v$ who bids $b$, her payoff is $v-b$ if $b > b'$, where $b'$ is the highest bid among his opponents, and her payoff if she loses is $b'/(n-1)$ if $b < b'$. Her expected profit from the bid $b$ can therefore be written as

$$(v_i - b) G_i(b) + \frac{1}{n-1} \int_b^{\bar{b}} x \, dG_i(x),$$

where $\bar{b}$ is the maximum of others' possible bids.

**Proposition 1.** *In a sealed-bid first-price auction in which the winner's payment is distributed evenly among losers, an equilibrium in which bidders with the same type follow the same bidding strategy, is defined by, for each bidder of the same type as bidder* $i$*,*

$$-G_i(b) + \left( \alpha_i(b) - \frac{n}{n-1} b \right) g_i(b) = 0.$$

*and boundary conditions* $\beta_i(0) = \beta_j(0)$ *and* $\beta_i(\bar{v}) = \beta_j(\bar{v})$ *where* $i \neq j$.[2]

**Example 1.** Suppose there are two bidders, namely strong bidder and weak bidder. The strong and weak bidders' valuations are distributed according to the beta distribution with parameters (2,1) and (1,2), respectively. The triangular-shaped probability densities of their valuations are shown in Figure 1, and their equilibrium bidding strategies are shown in Figure 2. Observe that their bids are the same when their values are 0 or 1, but for intermediate values the weak bidder bids more than the strong bidder with the same valuation.

---

[2] This is a system of simultaneous first-order ordinary differential equations, one for each type. A general procedure is to make the substitutions $\gamma_i(v_1) = \alpha_i(\beta_1(v_1))$ for types $i$ other than type 1, and use the properties that the derivatives are $\alpha'_1 = 1/\beta'_1$ and $\alpha'_i = \gamma'_i / \beta'_1$. Thus $\gamma_i(v_1)$ is $i$'s valuation such that she bids the same as a bidder of type 1 does when her value is $v_1$. Thus $v_1$ becomes the variable in the differential equations for the function $\beta_1(v_1)$ and the functions $\gamma_i(v_1)$ for types $i$ different than type 1. The boundary conditions are then that each $\gamma_i(0) = 0$ and $\gamma_i(\bar{v}) = \bar{v}$.

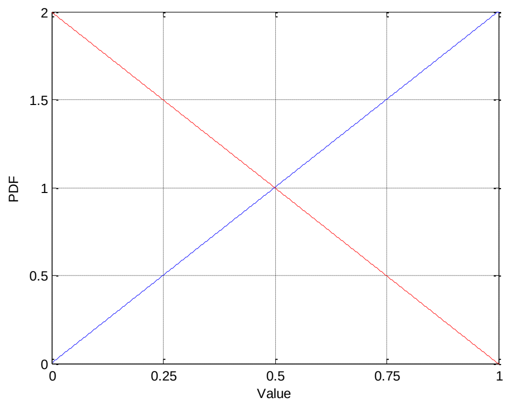


Figure 1. Probability densities of beta distribution with parameters (2,1) and (1,2), shown in blue and red lines, respectively

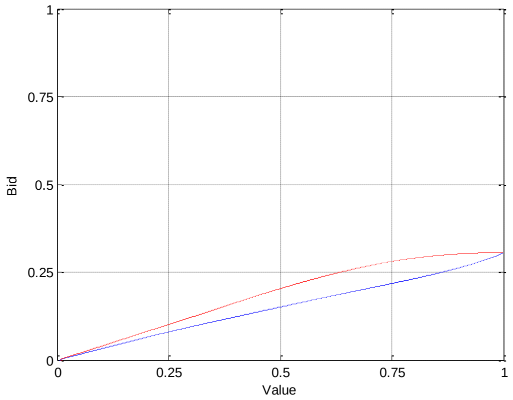


Figure 2. Bid functions of strong (blue) and weak (red) bidders in asymmetric first-price auction

## 2.2 Symmetric bidders in a first-price auction

Now we specialize to the case that the bidders have the same distribution of valuations, and each bidder uses the same bidding strategy $\beta(v)$ as a function of her valuation $v$.

From the perspective of any one bidder with value $v$ who bids $b=\beta(v)$, her payoff if she wins is $v-b$ and her payoff if she loses is $\beta(u)/(n-1)$, where $u$ is the random variable that is the maximum of $n-1$ independent draws from the distribution $F$ (hence has the cumulative $G=F^{n-1}$), and she wins if $b(v)>b(u)$. Therefore her expected profit when her value is $v$ and she bids $b$ is

$$(v-b)G(\alpha(b))+\int_{\alpha(b)}^{\bar{v}}\frac{\beta(u)}{n-1}dG(u).$$

**Proposition 2.** *In a symmetric-bidder sealed-bid first-price auction in which the winner's payment is distributed evenly among losers, a symmetric equilibrium strategy is given by*

$$\beta(v)=\frac{n-1}{nF(v)^n}\int_0^v xdF(x)^n=\frac{n-1}{n}\left(v-\int_0^v F(x)^n\,dx\right)$$

That is, the bid is the fraction $(n-1)/n$ of the expectation of the maximum of $n$ draws from the distribution $F$ conditional on the maximum being less than $v$.

**Example 2.** Suppose $F(v)=v$. Then the equilibrium bidding strategy is

$$\beta(v)=\frac{n-1}{n+1}v,$$

which yields a bidder with value $v$ the expected net profit

$$\pi(v)=\frac{1}{n}\left(v^n+\frac{n-1}{n+1}\right).$$

The expected winning bid, averaged over all possible valuations, is

$$\bar{p}=\frac{n(n-1)}{(n+1)^2}.$$

The expected gain from trade is $n/(n+1)$, of which each bidder's share *ex ante* averaged over all possible valuations is $E[\pi(v)]=1/(n+1)$.

**Example 3.** Suppose each of two bidders has the beta distribution with parameters (2,2). The density of their valuations is shown in Figure 3, and the equilibrium bidding strategy in Figure 4. The formula for the equilibrium bidding strategy is

$$\beta(v)=\frac{v^5(126+5v(12v-35))}{35(3(1-v)v^2+v^3)^2}.$$

The expected profit of a bidder with valuation $v$ is

$$\pi(v)=\frac{13}{70}+v^3-\frac{1}{2}v^4.$$

We will see later that the winner's expected payment of 0.248 is less than the expected payment of 0.263 in a second-price auction with the same distribution of the bidders' valuations; nevertheless, each bidder's expected profit $\pi(v)$ is the same in the two auction formats.

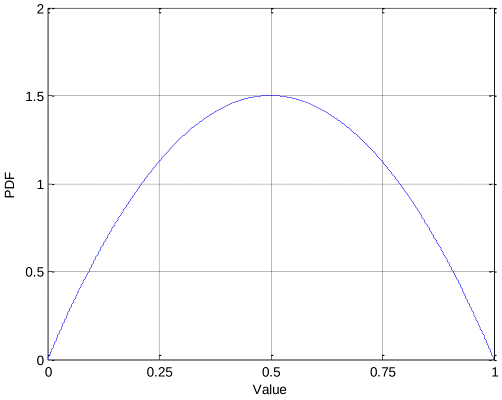


Figure 3. Probability density function of Beta distribution with parameters (2,2)

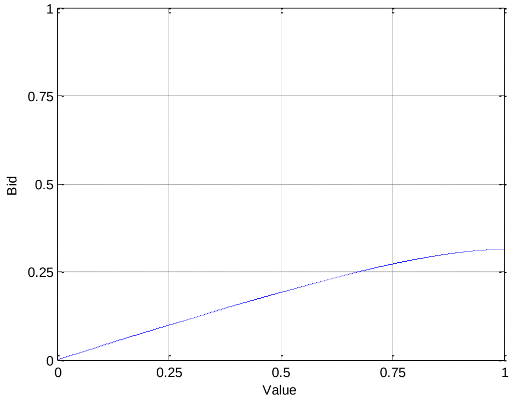


Figure 4. Bid function of a bidder with Beta distribution with parameter (2,2)

## 2.3 Asymmetric bidders in a second-price auction

In a second-price auction, from the perspective of any one bidder with value $v$ who bids $b$, her payoff is $v-b'$ if $b>b'$, where $b'$ is the highest bid among his opponents, and her payoff if she loses is $\max\{b,b''\}/(n-1)$ if $b<b'$, where $b''$ is the second-highest bid among his opponents.

Due to the long formulas that result, for simplicity here we address only the case of two types. Let $G_{ij}(b)=F_1(\alpha_1(b))^{m_1-i}F_2(\alpha_2(b))^{m_2-j}$. Then, the expected payoff of a bidder of type 1 whose value is $v$ and she bids $b\geq\underline{b}$ where $\underline{b}$ is the least bid among his opponents, is

$$\Pi_1(v,b)=\int_{\underline{b}}^{b}(v-b')dG_{10}(b')+\frac{1}{n-1}\int_b^1\left(bG_{20}(b)+\int_b^{b'}x\,dG_{20}(x)\right)(m_1-1)dF_1(\alpha_1(b'))$$
$$+\frac{1}{n-1}\int_b^1\left(bG_{11}(b)+\int_b^{b'}x\,dG_{11}(x)\right)(m_2)\,dF_2(\alpha_2(b'))$$

**Proposition 3.** *In a two-type sealed-bid second-price auction in which the winner's payment is distributed evenly among losers, a symmetric equilibrium is defined by,*

$$0=(\alpha_1-b)\left(m_2F_1f_2\alpha_2'+(m_1-1)F_2f_1\alpha_1'\right)+\frac{m_1-1}{n-1}F_2(1-F_1-bf_1\alpha_1')+\frac{m_2}{n-1}F_1(1-F_2-bf_2\alpha_2').$$

and

$$0=(\alpha_2-b)\left(m_1F_2f_1\alpha_1'+(m_2-1)F_1f_2\alpha_2'\right)+\frac{m_1}{n-1}F_2(1-F_1-bf_1\alpha_1')+\frac{m_2-1}{n-1}F_1(1-F_2-bf_2\alpha_2')$$

*and boundary conditions* $\beta_1(0)=\beta_2(0)$ *and* $\beta_1(\bar{v})=\beta_2(\bar{v})$. *Note that function arguments are omitted to shorten the equations.*

**Example 4.** As in Example 1 for a first-price auction, Suppose there are two bidders, strong and weak bidders. The strong and weak bidders' valuations are distributed according to the beta distribution with parameters (2,1) and (1,2), respectively. Their bidding strategies in a second-price auction are shown in Figure 6.

Note that the strong bidder is more likely to bid lower than the weak bidder, for the same values. Also, each bidder bids more than her value when her value is low. The evident motive is to drive up the price paid by the winning bidder.

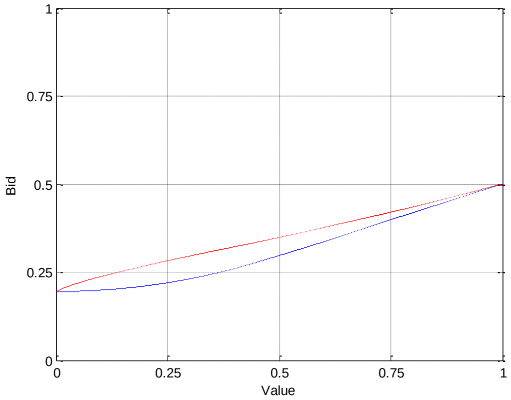


Figure 6. Bid functions of strong (blue) and weak (red) bidders in asymmetric second-price auction

## 2.4 Symmetric bidders in a second-price auction

Now we specialize to the case that the bidders have the same distribution of valuations, and each bidder uses the same bidding strategy $\beta(v)$ as a function of her valuation $v$.

In a second-price auction, from the perspective of any one bidder with value $v$ who bids $b=\beta(v)$, her payoff if she wins is $v-\beta(u)$ and her payoff if she loses is $\max\{b,\beta(w)\}/(n-1)$, where $w$ is the random variable that is the maximum of $n-2$ independent draws from the distribution $F$, and she wins if $b(v)>b(u)$. Hence her expected payoff is

$$\int_0^{\alpha(b)} v-\beta(u)\,dF(u)^{n-1}+(n-1)\int_{\alpha(b)}^{\bar{v}}\left(\int_0^{\alpha(b)}\frac{b}{n-1}dF(w)^{n-2}+\int_{\alpha(b)}^{u}\frac{\beta(w)}{n-1}dF(w)^{n-2}\right)dF(u).$$

**Proposition 4.** *In a symmetric-bidder sealed-bid second-price auction in which the winner's payment is distributed evenly among losers, a symmetric equilibrium strategy is given by*

$$\beta(v) = -\frac{n-1}{n(1-F(v))^n}\int_v^{\bar{v}} x d(1-F(x))^n = \frac{n-1}{n}\left(v + \frac{1}{(1-F(v))^n}\int_v^{\bar{v}} (1-F(x))^n\, dx\right).$$

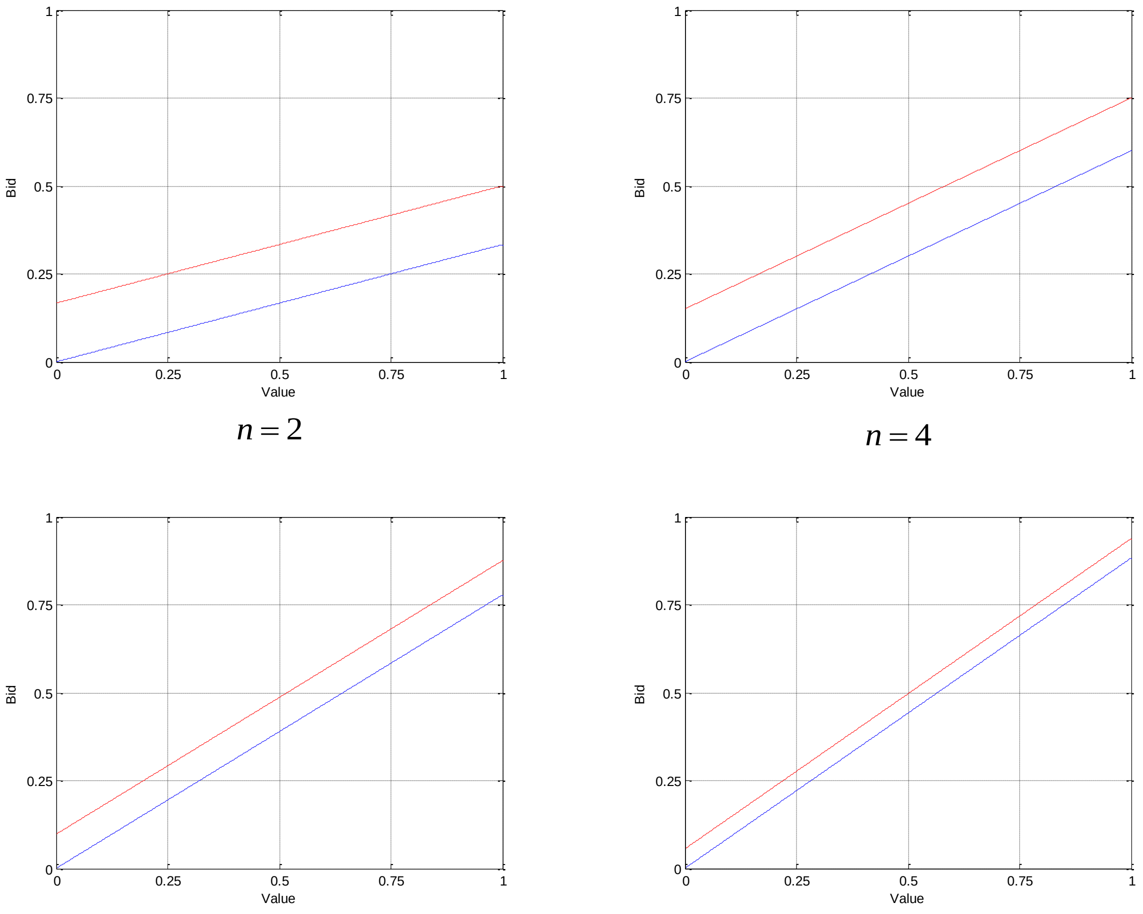
**Example 6.** Suppose $F(v) = v$. Then

$$\beta(v) = \frac{n-1}{n+1}\left(\frac{1}{n} + v\right),$$

Observe that $\beta(0) = \frac{1}{n+1} \times \frac{n-1}{n}$ and $\beta(1) = \frac{n-1}{n}$, and the strategy is the line between these two extreme points. Note especially that $\beta(v) > v$ if $v < \frac{n-1}{n} \times \frac{1}{2}$. That is, as in the asymmetric case of a second-price auction, one with a low valuation bids more than her value in view of the prospect of raising the price paid by the winner.

## 2.5 Comparison of first- and second-price auctions

For first-price and second-price auctions, Figure 7 compares the equilibrium bidding strategies and Figure 8 compares expected profits for various numbers of bidders, $n = 2, 4, 8, 16$.



$n = 2$ $n = 4$

$n = 8$ $n = 16$

Figure 7. Bid functions of strong (blue) and weak (red) bidders in uniform first- and second-price auctions [[4 lines?]]

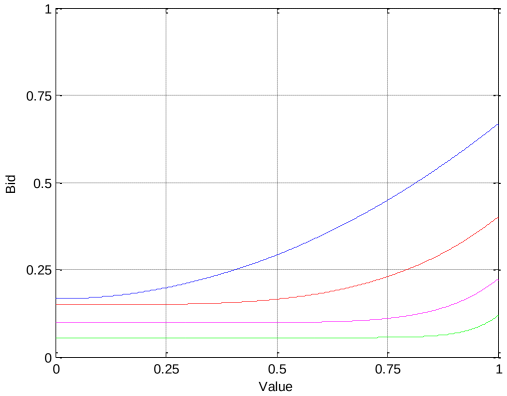


Figure 8. Expected profits in uniform auctions with 2 (blue), 4 (red), 8 (purple) and 16 (green) bidders

Although the bidding strategies for first-price and second-price auctions differ (the latter being higher), and also the expected payment of the winner differs (again, higher for a second-price auction), the expected profit of a bidder is the same in the two auction formats, namely

$$\pi(v) = \frac{(n-1)+(n+1)v^n}{n(n+1)}.$$

**Example 7.** As in Example 3, suppose each of two bidders has the beta distribution with parameters (2,2). The equilibrium bidding strategy in this case is

$$\beta(v) = \frac{13+2v(26+65v+60v^2)}{70(1+2v)^2},$$

as shown in Figure 9. Again, a bidder's expected profit is the same as in a first-price auction, namely

$$\pi(v) = \frac{13}{70} + v^3 - \frac{1}{2}v^4.$$

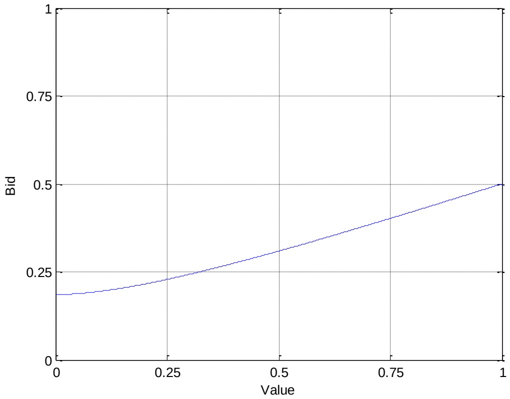


Figure 9. Bid function in asymmetric second-price auction

To summarize we have the following results.

**Proposition 5.** *Suppose (1) each bidder's value is drawn independently from the uniform distribution on* $[0,\bar{v}]$*, (2) each bidder seeks to maximize dollar profit, and (3) the high bidder wins and non-high bidders share the winner's payment equally. Then under either the first-price or second-price pricing rules there is a unique equilibrium, the outcome is ex post efficient, and each bidder's profit is invariant to the pricing rule (revenue equivalence).*

**Proof of Proposition 5.** Direct calculation results in a unique increasing equilibrium. Efficiency then is obvious. Revenue equivalence holds because the interim payment of the lowest-value bidder is invariant to the pricing rule. □

**Theorem 1.** *Suppose (1) each bidder's value is drawn independently from the same distribution F with positive density f on* $[0,\bar{v}]$*, (2) each bidder seeks to maximize dollar profit, and (3) the high bidder wins and non-high bidders share the winner's payment equally. Consider any pricing rule that results in a strictly increasing equilibrium bid function. Then the outcome is ex post efficient. However, the expected buyer payment depends on the pricing rule (revenue equivalence fails).*

**Proof of Theorem 1.** Efficiency is obvious from symmetry, the high-bid-wins rule, and the strictly increasing equilibrium bid function. Revenue equivalence does not hold because the interim payment of the lowest-value bidder is non-zero and depends on the pricing rule. This is shown from direct calculation. For example, consider an auction with three bidders whose values are distributed according to the distribution $F(v) = v^2$. The expected profits of a bidder with zero value differ in first- and second-price auctions as shown in Figure 10. □

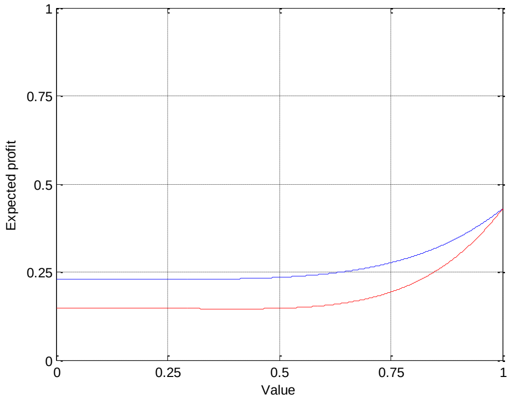


Figure 10. Expected profit for a bidder with $F(v) = v^2$, three bidders, and first-price (blue) or second-price (red)

## 3 Model with affiliated value

We consider the general symmetric model of a first-price applicant auction with affiliated signals and values, as in Milgrom and Weber (1982).

Let $F(y \mid x)$ be the distribution function of a signal $y$ given a bidder's signal $x$ and let $f(y \mid x)$ be its associated density function. Let $v(x,t)$ be the conditional expectation of the value obtained by the winner given his signal $x$ and the highest signal $t$ among the $n-1$ other bidders. Also, let $G(t \mid x)$ be the conditional distribution function of the highest signal $t$ among the $n-1$ other bidders given a signal $x$, and let $g(t\,|\,x)$ be its associated density. In addition, let $H(s\,|\,x,t)$ be the conditional distribution function of the second-highest signal $s$ among the $n-1$ other bidders given signals $x$ and $t$ and let $h(s\,|\,x,t)$ be its associated density.

If $\beta$ is the bidding strategy used by all bidders, and $\beta$ is increasing and differentiable with inverse function $\alpha$, then for any one bidder with signal $x$ his bid $b=\beta(x)$ must maximize the bidder's expected profit.

## 3.1 General symmetric first-price auction

A bidder's expected profit is defined as follows.

$$\int_0^{\alpha(b)} \big(v(x,t)-b\big)\,g(t\,|\,x)\,dt+\frac{1}{n-1}\int_{\alpha(b)}^{\infty}\beta(t)g(t\,|\,x)\,dt.$$

**Proposition 6.** *In a general sealed-bid first-price auction in which the winner's payment is distributed evenly among losers, a symmetric equilibrium strategy when the boundary condition is* $\beta(0)=v(0,0)=0$*, is defined by,*

$$\beta(x)=\frac{n-1}{n}\int_0^x v(t,t)d\theta(t\,|\,x)=\frac{n-1}{n}v(x,x)-\frac{n-1}{n}\int_0^x \theta(t\,|\,x)\,dv(t,t),$$

*and*

$$\theta(t\,|\,x)=\exp\left\{-\int_t^x \frac{n}{n-1}\frac{g(t\,|\,t)}{G(t\,|\,t)}dt\right\}.$$

**Example 4.** Suppose that the realized value is $V=\sum_{i=1}^{n} x_i\,/\,n$, the same for all $n$ bidders. Assume that the signals $x_i$ are uniformly, independently and identically distributed on $[0,1]$. Then,

$$\beta(x)=\left(\frac{1}{2}-\frac{1}{n(n+1)}\right)x.$$

Thus, $\beta(x)=\frac{20}{60}x,\frac{25}{60}x,\frac{27}{60}x,\ldots$ , when *n* = 2, 3, 4, … and $\beta(x)$ converges to $x/2$ as $n$ goes to infinity. Figure 5 shows bid functions with 2, 4, 8 and 16 bidders.

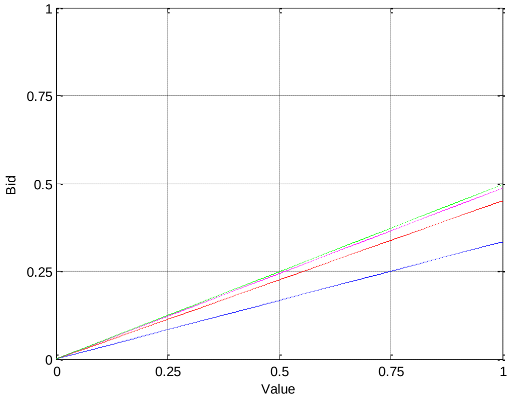


Figure 5. Bid functions in general symmetric first-price auctions with 2 (blue), 4 (red), 8 (purple) and 16 (green) bidders

## 3.2 General symmetric second-price auction

A bidder's expected profit is defined as follows.

$$\int_0^{\alpha(b)} (v(x,t)-\beta(t))g(t\,|\,x)dt+(n-1)\int_{\alpha(b)}^{\bar{x}}\left(\int_0^{\alpha(b)} \frac{b}{n-1}h(s\,|\,x,t)ds+\int_{\alpha(b)}^{t}\frac{\beta(s)}{n-1}h(s\,|\,x,t)ds\right)f(t\,|\,x)dt$$

**Proposition 7.** *In a general sealed-bid second-price auction in which the winner's payment is distributed evenly among losers, a symmetric equilibrium strategy is defined by*

$$\beta(x)=\int_x^{\bar{x}} v(t,t)\theta(t\,|\,x)\frac{g(t\,|\,t)}{\bar{H}(t)}dt,$$

*and*

$$\theta(t\,|\,x)=\exp\left\{-\int_x^s \frac{g(t\,|\,t)+f(t\,|\,t)H(t\,|\,t,t)}{\bar{H}(t)}dt\right\},$$

where $\bar{H}(x)=\int_x^{\bar{x}} H(x\,|\,x,t)f(t\,|\,x)dt$.

**Example 5.** Suppose that the realized value is $V=\sum_{i=1}^{n} x_i/n$, the same for all $n$ bidders. Assume that the signals $x_i$ are uniformly, independently and identically distributed on $[0,1]$. Then,

$$\beta(x)=\frac{(n+2)(n-1)}{2n(n+1)}(\frac{1}{n}+x)$$

Thus, $\beta(x)=\frac{1}{6}+\frac{1}{3}x,\frac{5}{36}+\frac{1}{12}x,\frac{9}{80}+\frac{1}{20}x,\dots$ , when *n* = 2, 3, 4, … and $\beta(x)$ converges to $x/2$ as $n$ goes to infinity. Figure 5 shows bid functions with 2, 4, 8 and 16 bidders.

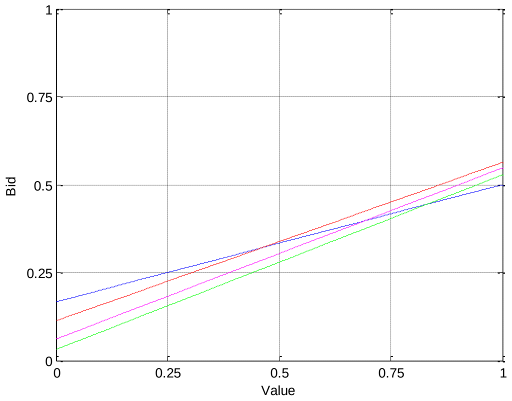


**Figure 5. Bid functions in general symmetric second-price auctions with 2 (blue), 4 (red), 8 (purple) and 16 (green) bidders**

## 4 Proposed auction designs for applicant auction

Our theoretical analysis above has been focused on auctioning a single domain. For the ICANN application, a large number of domains, roughly 145, need to be auctioned. Many bidders are bidding for multiple domains, have budget constraints, and their values depend on the clearing prices of other domains. Therefore, in addition to the pricing rule, other specific details of the auction design matter.

We propose two designs for the Applicant Auction: A first-price auction in which individual domains or batches of domains are sold sequentially, and a simultaneous second-price auction in which all domains are sold simultaneously.

In the *sequential* auction each domain is auctioned in sequence in a sealed-bid first-price auction. The high bidder wins the domain and pays its bid to the losing bidders, with the total payment divided equally among them.[3] After each auction, the auction system reports the high bid. The auction system also presents to each participant its own current winnings and its current settlement balance, which reflects payments for the domains it wins and receipts for domains it lost. The auction schedule is also displayed. For practical reasons, sets of domains may be grouped into batches which are sold simultaneously. This change shortens the auction, with limited impact on results. In the ideal case, in each batch, each company bids on at most one domain. This eliminates a possible exposure problem arising when a budget constrained bidder must bid for two domains at once of which she can only afford one. If such batching is not possible (as is the case in the ICANN setting, due to Donuts bidding on a majority of the contested domains), the next best option is to distribute the number of domains each bidder bids on in each round as evenly as possible.

---

[3] Variations on the division of the payment are certainly possible and will be considered in our analysis. For example, a natural rule would be to divide the winner's payment in proportion to the losing bids; thus, with $n$ bidders and bids $b_1 > b_2 > \ldots > b_n$, the winning bidder 1 pays losing bidder $i$ an amount $b_1 \times b_i / (b_2 + \ldots + b_n)$. The advantage of this approach is that it rewards those with higher values for the domain more. It, however, has a serious disadvantage: it creates an incentive for each bidder to bid more than its true value, and the incentive to bid more is largest for those with low values. This distortion causes the auction to be inefficient. In contrast, the equal-payment approach means that the payment to each loser does not depend on its bid. The outcome is fully efficient in the simplest case described later.

In the *simultaneous* auction, all domains are auctioned simultaneously in an ascending process. This gives the bidders richer possibilities for substituting among domains and bidding for complementary sets of domains. Second, as an ascending price process, the system allows frequent reporting of demand information, and thus facilitates price and allocation discovery through the process. Bidders are provided with relevant information that the bidders can then use when placing subsequent bids. The approach is commonly used for spectrum auctions, but is also used in many other industries, such as diamonds, gas, and electricity. It is particularly applicable in this auction since there is significant uncertainty regarding the overall value of top-level domains.

As mentioned, the simultaneous ascending auction occurs over a sequence of rounds. All domains are auctioned simultaneously. Each has a price associated with it. Before each round, the auctioneer announces a start of round price and an end of round price for each domain for which there is still competition. The end of round price is higher than the start of round price by the bid increment, which is set by the auctioneer in each round based on the level of competition. Each round, bidders who are still in the auction for a domain can update their proxy bid for the domain.

At the end of each round, if the demand for a domain is no greater than one, the highest bidder for that domain wins and pays the second highest price. The winner's payment is split equally among the other applicants for the domain, and all bidders' deposit amounts are updated to reflect the change.

If the demand is two or greater, the auction continues for that domain and another round is scheduled, but bidders whose proxy bid for a domain was lower than the end of round price of a domain are eliminated from the auction for that domain. Before the start of the next round, the auctioneer announces, along with start and end prices for the next round, the excess demand for each domain.

This process continues until all domains have closed.

## 5 Experimental testing of proposed designs

Experiment subjects were PhD students at the University of Maryland in Economics, Computer Science, and Computer Engineering, with training in game theory and auction theory. Subjects were offered a payment of about $200 per session. The actually dollar payment was proportionate to the bidder's total profits, which depends on all the bids and the bidder's values. Actual total payments had a mean of $413, standard deviation of $32, a minimum of $338, and a maximum of $476. Each subject participated in two sessions; each session lasted between 4 and 5.5 hours with a food break in the middle of each session.

The framing and subjects were chosen to closely match the actual setting. Based on ICANN's publicly downloadable data, 16 bidders were selected to allow auctioning 87 domain names for which there was unanimous participation. Of the 16 bidders, the 8 bidders bidding on the fewest domains were simulated using software; that is, these 8 bidders always bid their equilibrium bids. The other 8 bidders were assigned randomly to human experiment subjects, resulting in 198 of the 225 applications being bid on by humans. 3 of the 8 human bidders were given a budget constraint for all auctions; however, it was only binding in the simultaneous case, reflecting the fact that in a sequential auction, bidders do not have to bid on as many domains at once and are thus less likely to face budget constraints (unless they end up winning a large number of domains).

Values for bidders were drawn randomly according to two different probability distributions: For the "symmetric" case, values were drawn from the Uniform distribution, scaled so that the resulting numbers closely matched a realistic estimate for the actual ICANN auction setting. "Asymmetric" values were scaled similarly, but generated by drawing from beta (1,2) or beta (2,1), depending on whether the bidder was marked as weak or strong, respectively. A fixed set of 3 bidders was marked "Strong", the other ones "Weak". To reduce variance across identical treatments and sequential-simultaneous treatments, 4 fixed random data streams were used, in such a way that no individual experiment subject was ever exposed to the same data stream.

Two sets of two 4-hour experiment sessions were run in October 2012 to cover symmetric values and asymmetric values, for the simultaneous and sequential auction design. In each session, two auctions were conducted. Bidders were given their bidding information, including instructions and their bidder's values, four hours prior to the auction.

Both auction designs were implemented in software, using a state of the art commercial web-based auction framework. The user interface was custom written for the auction designs proposed, to allow experiment subjects to focus on the auction. In both cases, subjects were able to enter proxy bids, and the software kept track of the bidder's values to simplify the bidding process and eliminate sources of errors by the bidders.

## 6 Experimental results

Figure 11 shows efficiency measured as ratio of realized value to potential value. Both auction formats, regardless of bidder asymmetry, realize on average 98% of the potential value and thus highly efficient. Efficiency of the sequential auction is not significantly different from that of simultaneous auction.

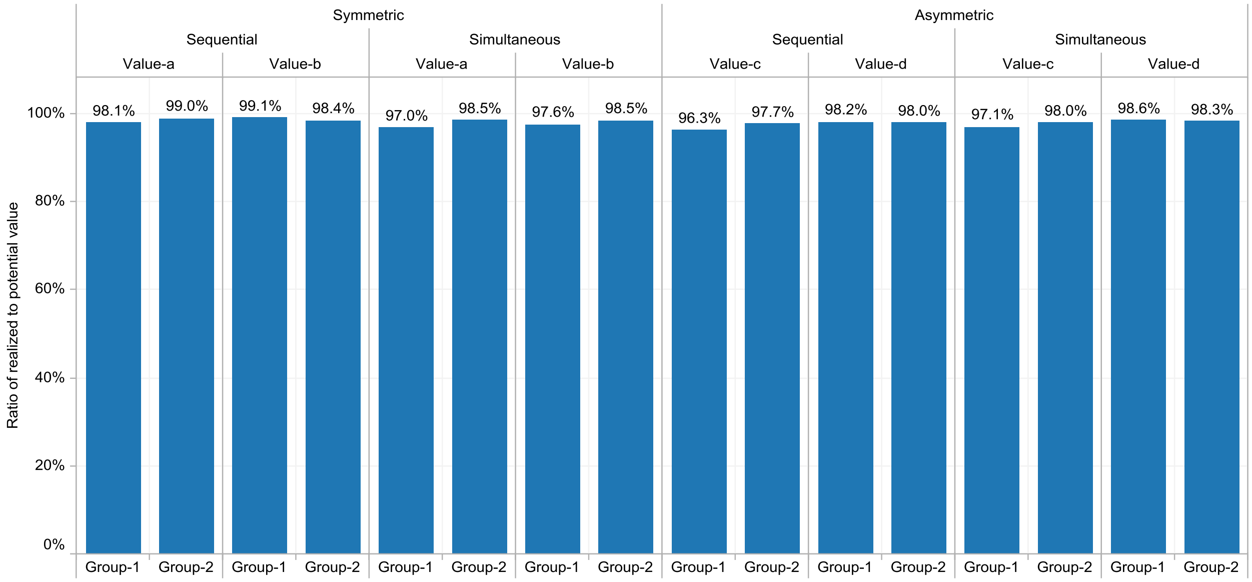


Figure 11. Efficiency of each treatment

Figure 12 shows buyer share and seller share—a ratio between buyer and seller's payoffs to realized value, respectively. The split among buyer and sellers is about the same in all cases.

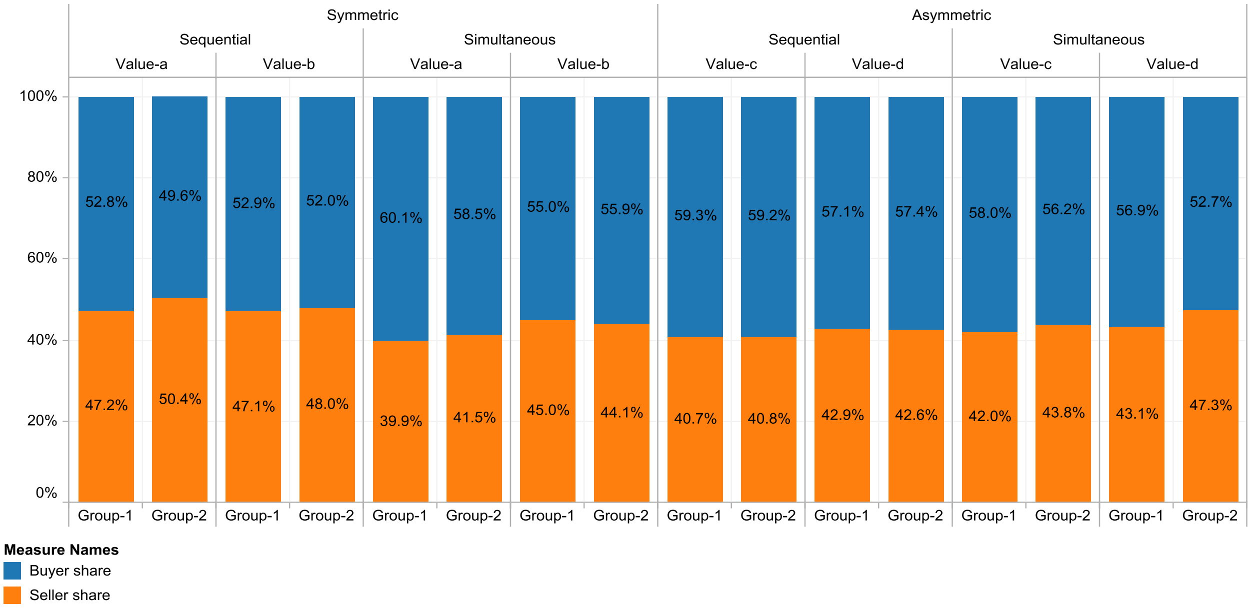


Figure 12. Buyer and seller's shares

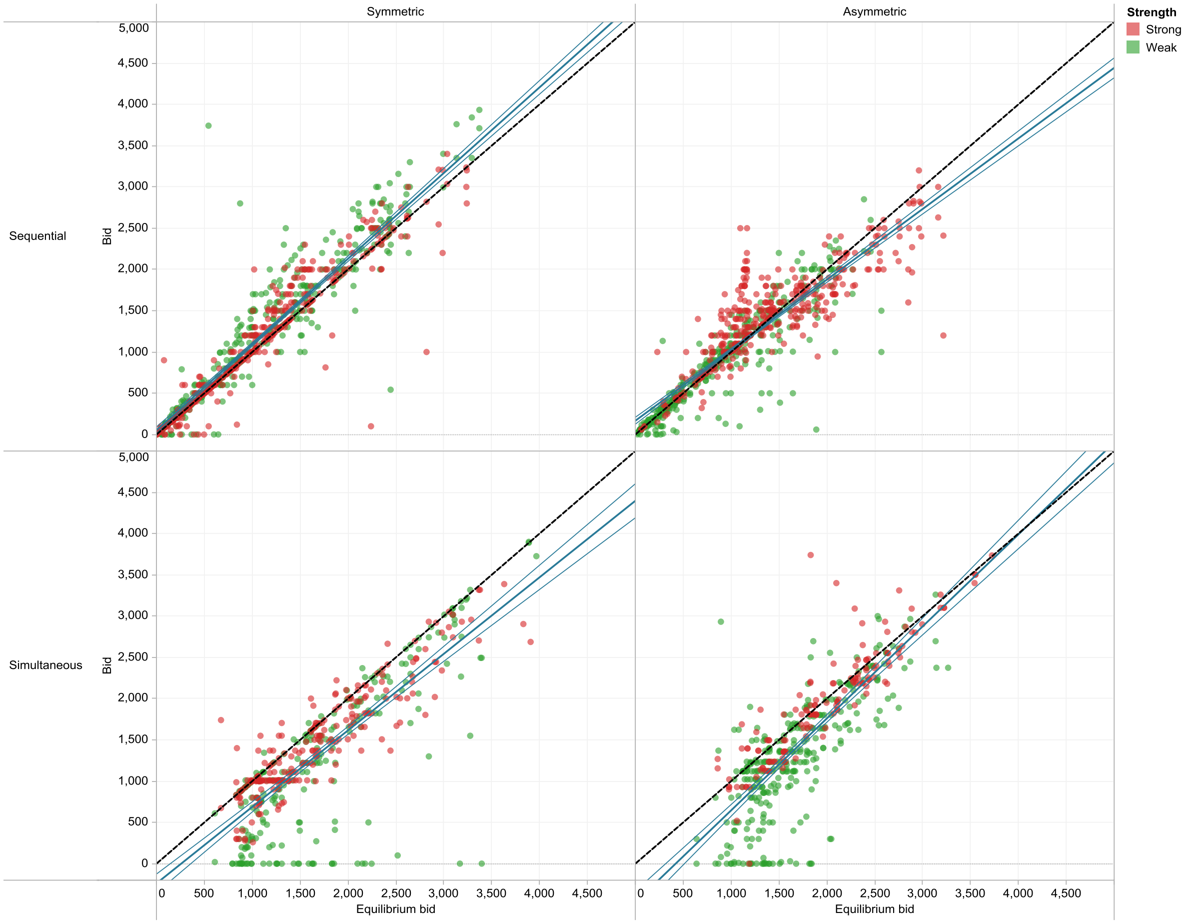


Figure 13. Actual and equilibrium bids

Figure 13 plots actual against equilibrium bids. The black dash line is a 45-degree line. The blue lines are trend with 5% confidence band. In sequential auction, bidders tend to overbid in symmetric case and underbid in asymmetric case. In simultaneous auction, bidders tend to underbid in both cases.

## 7 Conclusion

A theme of our results is that the basic tools of auction theory can be used straightforwardly to study applicant auctions in which the winner's payment is divided among the losers. Nevertheless, the qualitative features of the equilibrium bidding strategies include novel aspects. Most dramatic is that in a second-price auction a bidder with a low valuation has an incentive to bid more than her valuation in order to drive up the winner's payment. Nevertheless, when the bidders are symmetric the predicted outcome is efficient and each bidder is indifferent between the two auction formats regardless of her valuation. Even when bidders are symmetric ex ante, the outcome is highly efficient. Our experiments involving PhD students are consistent with the theory.

## References

Cramton, Peter, Robert Gibbons, and Paul Klemperer (1987), "Dissolving a Partnership Efficiently," *Econometrica*, 55, 615-632.

McAfee, R. Preston and John McMillan (1992), "Bidding Rings," *American Economic Review*, 82, 579-599.

Milgrom, Paul and Robert J. Weber (1982), "A Theory of Auctions and Competitive Bidding," *Econometrica*, 50, 1089-1122.

## Appendix A: Proofs

**Proof of Proposition 1.** For $b$ to be optimal it is necessary that the first-order condition is satisfied, for each $i$,

$$-G_i(b)+(v_i-b)g_i(b)-\frac{1}{n-1}bg_i(b)=0.$$

Proposition 1 can be obtained by replacing $v_i=\alpha_i(b)$. □

**Proof of Proposition 2.** For $b=\beta(v)$ to be optimal it is necessary that the first-order condition is satisfied

$$-G(\alpha(b))+(v-b)g(\alpha(b))\alpha'(b)-\frac{\beta(\alpha(b))}{n-1}g(\alpha(b))\alpha'(b)=0,$$

evaluated at $b=\beta(v)$, where $\alpha(b)=v$, $\beta(\alpha(b))=\beta(v)$ and $\alpha'(\beta(v))=1/\beta'(v)$. Thus, the condition reduces to

$$\beta'(v)+\frac{n}{n-1}\cdot\frac{g(v)}{G(v)}\beta(v)=v\frac{g(v)}{G(v)}.$$

With a boundary condition, $\beta(0)=0$, then we can derive the explicit solution as

$$\beta(v)=\frac{n-1}{nF(v)^n}\int_0^v t\,dF(t)^n.$$

Integrating by-part yields the bid function in Proposition 2. □

**Proof of Proposition 3.** For the bid $b$ to be optimal it is necessary that the first-order condition is satisfied, at $\alpha_1(b)=v$,

$$0=(\alpha_1-b)g_{10}+\frac{m_1-1}{n-1}G_{20}(1-F_1-bf_1\alpha_1')+\frac{m_2}{n-1}G_{11}(1-F_2-bf_2\alpha_2'),$$

and, at $\alpha_2(b)=v$,

$$0=(\alpha_2-b)g_{20}+\frac{m_2-1}{n-1}G_{10}(1-F_2-bf_2\alpha_2')+\frac{m_1}{n-1}G_{22}(1-F_1-bf_1\alpha_1').$$

Divide the first and the second conditions by $G_{21}$ and $G_{12}$, respectively, to get the equivalent condition. □

**Proof of Proposition 4.** For the bid $b$ to be optimal it is necessary that the first-order condition is satisfied (after removing a factor $F^{n-3}(\alpha(b))$):

$$
\begin{aligned}
0 &= (v-\beta(\alpha(b)))(n-1)F(\alpha(b))\,f(\alpha(b))\alpha'(b)+F(\alpha(b))(1-F(\alpha(b)))\\
&\quad +b(n-2)(1-F(\alpha(b)))\,f(\alpha(b))\alpha'(b)-bF(\alpha(b))\,f(\alpha(b))\alpha'(b)\\
&\quad -\beta(v)(n-2)(1-F(\alpha(b)))\,f(\alpha(b))\alpha'(b),
\end{aligned}
$$

where an equilibrium requires that $b=\beta(v)$, $\alpha'=1/\beta'(v)$, and $v$ is the argument of $F$ and $f$. This yields the characterization

$$\beta'(v)-\frac{nf(v)}{1-F(v)}\beta(v)=-\frac{(n-1)f(v)}{1-F(v)}v.$$

If we suppose that $\beta(\bar{v})$ is bounded, then we can derive the explicit solution as shown in Proposition 4. □

**Proof of Proposition 6.** The necessary condition for a maximum is

$$0=-G(\alpha(b)\,|\,x)+\big(v(\alpha(b),t)-b\big)\,g(\alpha(b)\,|\,x)\alpha'(b)-\frac{1}{n-1}\beta(\alpha(b))g(\alpha(b)\,|\,x)\alpha'(b),$$

or, since $\beta(\alpha(b))=b$,

$$\beta'(x)+\frac{n}{n-1}\cdot\frac{g(x\,|\,x)}{G(x\,|\,x)}\beta(x)=v(x,x)\frac{g(x\,|\,x)}{G(x\,|\,x)}.$$

This is analogous to the necessary condition for an ordinary first-price auction except that the hazard rate in the second term is inflated by the factor $n/(n-1)$, which reflect the effect of dividing the winner's payment among the losers. Solving the differential equation and integrating by-part, together with the boundary condition, yield the equilibrium strategy. □

**Proof of Proposition 7.** The necessary condition for a maximum is

$$
\begin{aligned}
0 &= (v(x,x)-\beta(x))\frac{g(x\,|\,x)}{\beta'(x)}-(n-1)\left(\int_0^x\frac{b}{n-1}h(s\,|\,x,x)ds+\int_x^x\frac{\beta(s)}{n-1}h(s\,|\,x,x)dt\right)\frac{f(x\,|\,x)}{\beta'(x)}\\
&\quad +(n-1)\int_x^{\bar{x}}\left(\int_0^x\frac{1}{n-1}h(s\,|\,x,t)ds+\frac{\beta(x)}{n-1}\frac{h(x\,|\,x,t)}{\beta'(x)}-\frac{\beta(x)}{n-1}\frac{h(x\,|\,x,t)}{\beta'(x)}\right)f(t\,|\,x)dt,
\end{aligned}
$$

or, since $\beta(\alpha(b))=b$,

$$0=(v(x,x)-\beta(x))\frac{g(x\,|\,x)}{\beta'(x)}-\beta(x)H(x\,|\,x,x)\frac{f(x\,|\,x)}{\beta'(x)}+\bar{H}(x\,|\,x).$$

Suppose $\beta(\bar{x})$ is bounded, solving the differential equation yields the equilibrium bidding strategy. □

## Appendix B: Bidder Instructions

### 1. Sequential First-Price Sealed-Bid Auction: Instructions to Bidders (Symmetric distribution)

Welcome to the Applicant Auction Experiment. In this experiment, you will participate in domain auctions as a bidder. The precise rules and procedures that govern the auctions are explained below.

Various foundations have provided funds for this research. The instructions are simple, and if you follow them carefully and make good decisions you can finish the experiment with a considerable amount of money, which will be paid to you in cash at the end of the experiment. Participants completing the session do not risk losing any money. The experiment will last about four hours.

Currency used in this experiment is Experimental Dollars (ED) in thousands. Throughout the experiment the dollar figures refer to this currency with "thousands" suppressed. At the end of the experiment your earnings will be converted into US Dollars using the conversion rates given below. You will be paid in cash at the end of the experiment. The more ED you earn, the more US Dollars you earn.

#### Auction setting

You are a bidder in four domain auctions that will be conducted in this experiment. In each auction, there are 16 bidders competing for 87 domains. Each bidder will be assigned: (i) a set of domains that the bidder has applied for, and (ii) their *private values* for these domains.

Bidders differ in the set of domains that they applied for and have different values for the same domains. The domains for each bidder are shown in the bidding tool discussed at the end of this instruction. Bidders cannot bid for domains they did not apply for.

In the experiment about eight bidders are played by human bidders, while the remaining bidders are played by computer bidders. You will be randomly assigned to one of the human bidders. The computer bidders follow an equilibrium bidding strategy for a simplified setting, as described below.

#### Values

Two auctions are conducted in this session. Both auctions are identical in structure, although the values are independent.

Each bidder's value for each domain is randomly and independently drawn from a *uniform distribution* on the interval [0, 5000], rounded to the nearest integer. These values are private—each bidder will know only her own value.

#### Auction rules

A Sequential First-Price Sealed-Bid Auction will be used throughout this session. All 87 domains will be sold in a sequence of first-price sealed-bid rounds. In each round, a small batch of domains will be auctioned simultaneously using the first-price sealed-bid format: for each domain, the high bidder wins and pays her bid. The winner's payment is split equally among the losing bidders. Ties are broken randomly.

The batching of domains, as well as the auction schedule for each round will be announced before the first round takes place.

You will be able to make bids on each of the domains you applied for. At the time you place your bid you will know the set of domains you applied for (and therefore can bid on) and the set of domains each of the other bidders applied for. Thus, you will know both the number of bidders and the other companies that applied for each domain. If you fail to place a bid in the time available—either before or during the round in which the particular domain is auctioned—a bid of zero is assumed.

After a round has ended, the winning bid amount will be disclosed, but not the identity of the winner.

## Profits

A bidder's total profit is the sum of the profits from all domains of interest. Due to the payment rule in this auction, along with the usual profit from the domains you have won, you also profit from the domains that you have lost.

- Profit from domain won:

$$\text{Profit}_{won} = \text{value} - \text{price}$$

- Profit from domain lost, where *n* is the initial number of bidders for the domain:

$$\text{Profit}_{lost} = \frac{\text{winner's payment}}{\text{n} - 1}$$

### *Examples*

Suppose that your valuation for the domain is 4,500 and you win it at a price of 4,000. Then your profit from this domain is equal to 4,500 – 4,000 = 500 ED.

Suppose that you lose the domain, the initial number of bidders for that domain is 5, and the winner pays 4,000. Then your profit from this domain is equal to 4,000 / 4 = 1,000 ED.

## Deposit

Each bidder has an initial deposit. The size of the deposit determines the maximum bidding commitment the bidder can make. The total of active bids and winning payments cannot exceed five times the current deposit. As domains are sold, the payment received by the loser is added to the deposit amount.

The auction system will prevent a bidder from placing bids on a collection of domains that would cause the bidder's total commitment to exceed five times the bidder's current deposit.

## Bidding strategy

The sequential first-price sealed-bid auction allows the bidders to adopt complex bidding strategies. Below are some results from auction theory about single item auctions that may be relevant when devising your bidding strategy.

Before stating the results, here is some notation. There are $n$ bidders with bidder $i$ assigning a value of $V_i$ to the object. Each $V_i$ is drawn independently on the interval $[0, \bar{v}]$ according to the cumulative distribution function $F_i$ with a positive density $f_i$. ( $\bar{v} = 5000$ in the experiment.)

Recall that in the standard private-value setting where winning payments are retained by the auctioneer, the first-price auction has a unique symmetric equilibrium when each bidder's value is drawn from the same distribution *F* with positive density *f*. It is

$$b(v) = v - F(v)^{-(n-1)} \int_0^v F(u)^{n-1} du.$$

For the uniform distribution on the interval $[0, \bar{v}]$, this reduces to $b(v) = \frac{n-1}{n} v$. Thus with two bidders you bid one-half of your value.

Bidder incentives change in our setting where the winner's payment is shared equally among the losers. Notice that losing is made more attractive in this case, relative to the standard auction—the loser receives a share of the winner's payment, rather than 0.

With symmetric bidders with values independently drawn from the uniform distribution, there is a unique symmetric equilibrium for the first-price domain auction. It is

$$b(v) = \frac{n-1}{n+1} v.$$

## Bidding tool

In addition to the auction system, you will have a bidding tool, applicant-auction-tool-sequential.xlsx. All bidders have the same tool. The tool allows you to explore alternative bidding strategies. It includes all the information that is common knowledge: the domains, the bidders and which domains each can bid for, the equilibrium bid functions wherever the equilibrium is known (as described above). Note that there is a separate sheet for each auction. Be sure you are using the correct sheet for the particular auction.

To use the tool, you will need to go to the appropriate sheet. Each of the two auctions has a separate sheet—Symmetric1 and Symmetric2. Then sort the sheet by your bidder name and then by domain, so that all the domains you can bid for are listed first and in alphabetical order. Then you can paste your values into the sheet from the auction system by clicking on the Bidder Info button, selecting all domains and values in the window toward the bottom of the screen, then Ctrl-C to copy. Of course this step must be repeated for each auction. Be sure to save the Workbook once your values are pasted in. Also save your workbook at the end of each auction.

You can then use the tool to explore various bidding strategies. Once you are happy with your bids, you can enter them directly in the auction system, or if you have many bids, you can upload your bids. To upload bids, you must first create a bid upload file in .csv format. Then go to the auction system and click the Upload button on the Bidding screen to upload the bids. Be sure to check your uploaded bids carefully. Any errors can be corrected directly or through another upload.

Please note that you initially may not have sufficient money on deposit to bid as high as you would like on all of your domains. You may need to limit some bids early on in order to satisfy the limitation on bids coming from your limited deposit. You commitments from active bids and domains won can be at most five times your current deposit.

### Payment conversion

Your profits in each auction in ED currency is converted to the US Dollars by the formula

$$\text{Payment in US dollars} = \text{Profit in ED} \times \text{rate for role}$$

The payout rate for each role is given below:

| Bidder | Rate |
|---|---|
| Donuts | 0.12% |
| Minds+Machine | 0.27% |
| Google | 0.32% |
| Famous Four | 0.29% |
| Uniregistry | 0.27% |
| Afilias | 0.97% |
| Amazon | 0.44% |
| Radix | 0.92% |

At the end of the session you will receive your total US dollar payoff in cash. The conversion rates have been set so that each subject receives a payment of approximately US$400, regardless of role. The actual payment will be more or less than US$400 depending on the bids of the bidders in the auctions.

## 2. Simultaneous Ascending Clock Auction: Instructions to Bidders (Symmetric distribution)

Welcome to the Applicant Auction Experiment. In this experiment, you will participate in domain auctions as a bidder. The precise rules and procedures that govern the auctions are explained below.

Various foundations have provided funds for this research. The instructions are simple, and if you follow them carefully and make good decisions you can finish the experiment with a considerable amount of money, which will be paid to you in cash at the end of the experiment. Participants completing the session do not risk losing any money. The experiment will last about four hours.

Currency used in this experiment is Experimental Dollars (ED) in thousands. Throughout the experiment the dollar figures refer to this currency with “thousands” suppressed. At the end of the experiment your earnings will be converted into US Dollars using the conversion rates given below. You will be paid in cash at the end of the experiment. The more ED you earn, the more US Dollars you earn.

## Auction setting

You are a bidder in four domain auctions that will be conducted in this experiment. In each auction, there are 16 bidders competing for 87 domains. Each bidder will be assigned: (i) a set of domains that the bidder has applied for, and (ii) their *private values* for these domains.

Bidders differ in the set of domains that they applied for and have different values for the same domains. The domains for each bidder are shown in the bidding tool discussed at the end of this instruction. Bidders cannot bid for domains they did not apply for.

In the experiment about eight bidders are played by human bidders, while the remaining bidders are played by computer bidders. You will be randomly assigned to one of the human bidders. The computer bidders follow an equilibrium bidding strategy for a simplified setting, as described below.

## Values

Two auctions are conducted in this session. Both auctions are identical in structure, although the values are independent.

Each bidder's value for each domain is randomly and independently drawn from a *uniform distribution* on the interval [0, 5000], rounded to the nearest integer. These values are private—each bidder will know only her own value.

## Auction rules

A Simultaneous Ascending Clock Auction will be used throughout this session.

All 87 domains will be sold simultaneously in multiple rounds. In each round, for each domain, the number of active bidders is announced together with two prices: (i) the *minimum price to bid,* and (ii) the *minimum price to continue*. The *minimum price to bid* is where the auction has reached at the end of the last round (or $0 in the first round). You are already committed to a bid of at least this amount, which is why this is the lowest bid you may place. The *minimum price to continue* is the smallest bid that you may place in the current round in order to be given the opportunity to bid in the next round. Thus, for each domain of interest, the submitted bid indicates your decision to either exit in the current round with a bid that is between the *minimum price to bid* and the *minimum price to continue*, or continue with a bid that is at or above the *minimum bid to continue*, in which case you will be given the opportunity to continue bidding on the domain in the next round. In other words you may:

- *Exit* from a domain by choosing a bid that is less than the announced *minimum price to continue* for that round. A bidder cannot bid for a domain for which she has submitted an exit bid.
- You may *continue* to bid on a domain of interest by choosing a bid that is greater than or equal to the announced *minimum price to continue* for that round.

At the end of the round, the auction system will identify if the domain received multiple bids that are greater than or equal to the *minimum price to continue*. If so, the auction for that domain will proceed to the next round. The price for the domain will be increased by a percentage increment in the next round.

If there is only one or no bid that is greater than or equal to the *minimum price to continue* for a domain, the domain is won by the highest bidder. Ties are broken randomly.

The auction continues until there is no domain for which multiple bidders are active; that is, there is no excess demand, since all or all-but-one bidder has placed an exit bid for the domain at a price less than the *minimum price to continue*.

Pricing is based on a second-price rule: Each domain then is awarded to the highest bidder, who will pay the highest losing bid. Each losing bidder will receive an equal share of the winner's payment; that is, each loser receives the winner's payment divided by the number of losing bidders for the particular domain.

In each round, bidders need to submit their bids within the time allowed. If no action is taken for a domain, it will be assumed that the bidder has chosen to exit from that domain.

## Profits

A bidder's total profit is the sum of the profits from all domains of interest. Due to the payment rule in this auction, along with the usual profit from the domains you have won, you also profit from the domains that you have lost.

- Profit from domain won:

$$\text{Profit}_{won} = \text{value} - \text{price}$$

- Profit from domain lost, where *n* is the initial number of bidders for the domain:

$$\text{Profit}_{lost} = \frac{\text{winner's payment}}{\text{n} - 1}$$

### *Examples*

Suppose that your valuation for the domain is 4,500 and you win it at a price of 4,000. Then your profit from this domain is equal to 4,500 – 4,000 = 500 ED.

Suppose that you lose the domain, the initial number of bidders for that domain is 5, and the winner pays 4,000. Then your profit from this domain is equal to 4,000 / 4 = 1,000 ED.

## Deposit

Each bidder has an initial deposit. The size of the deposit determines the maximum bidding commitment the bidder can make. The total of active bids and winning payments cannot exceed five times the current deposit. As domains are sold, the payment received by the loser is added to the deposit amount. Also for domains that have not yet sold but for which the bidder has exited, the bidder's deposit is credited with the minimum payment that the bidder may receive once the domain is sold—this is the *minimum price to bid* in the current round.

The auction system will prevent a bidder from placing bids on a collection of domains that would cause the bidder's total commitment to exceed five times the bidder's current deposit.

## Bidding strategy

The simultaneous ascending clock auction allows the bidders to adopt complex bidding strategy. Below are some results from auction theory about single item auctions that may be relevant when devising your bidding strategy.

Before stating the results, here is some notation. There are $n$ bidders with bidder $i$ assigning a value of $V_i$ to the object. Each $V_i$ is drawn independently on the interval $[0, \bar{v}]$ according to the cumulative distribution function $F_i$ with a positive density $f_i$. ( $\bar{v} = 5000$ in the experiment.)

Recall that in the standard private-value setting where winning payments are retained by the auctioneer, the second-price and ascending clock auctions both have the same dominant strategy equilibrium: bid (up to) your private value, or $b(v) = v$.

Bidder incentives change in our setting where the winner's payment is shared equally among the losers. Notice that losing is made more attractive in this case, relative to the standard auction—the loser receives a share of the winner's payment, rather than 0.

With symmetric bidders with values independently drawn from the uniform distribution, there is a unique symmetric equilibrium for the second-price domain auction. It is

$$b(v) = \bar{v}\,\frac{(n-1)\left(n\dfrac{v}{\bar{v}}+1\right)}{n(n+1)}.$$

## Bidding tool

In addition to the auction system, you will have a bidding tool, applicant-auction-tool-simultaneous.xlsx. All bidders have the same tool. The tool allows you to explore alternative bidding strategies. It includes all the information that is common knowledge: the domains, the bidders and which domains each can bid for, the equilibrium bid functions wherever the equilibrium is known (as described above). Note that there is a separate sheet for each auction. Be sure you are using the correct sheet for the particular auction.

To use the tool, you will need to go to the appropriate sheet. Each of the two auctions has a separate sheet—Symmetric1 and Symmetric2. Then sort the sheet by your bidder name and then by domain, so that all the domains you can bid for are listed first and in alphabetical order. Then you can paste your values into the sheet from the auction system by clicking on the Bidder Info button, selecting all domains and values in the window toward the bottom of the screen, then Ctrl-C to copy. Of course this step must be repeated for each auction. Be sure to save the Workbook once your values are pasted in. Also save your workbook at the end of each auction.

You can then use the tool to explore various bidding strategies. Once you are happy with your bids, you can enter them directly in the auction system, or if you have many bids, you can upload your bids. To upload bids, you must first create a bid upload file in .csv format. Then go to the auction system and click the Upload button on the Bidding screen to upload the bids. Be sure to check your uploaded bids carefully. Any errors can be corrected directly or through another upload.

Please note that you initially may not have sufficient money on deposit to bid as high as you would like on all of your domains. You may need to limit some bids early on in order to satisfy the limitation on bids coming from your limited deposit. You commitments from active bids and domains won can be at most five times your current deposit.

### Payment conversion

Your profits in each auction in ED currency is converted to the US Dollars by the formula

$$\text{Payment in US dollars} = \text{Profit in ED} \times \text{rate for role}$$

The payout rate for each role is given below:

| Bidder | Rate |
|---|---|
| Donuts | 0.12% |
| Minds+Machine | 0.27% |
| Google | 0.33% |
| Famous Four | 0.29% |
| Uniregistry | 0.28% |
| Afilias | 0.99% |
| Amazon | 0.44% |
| Radix | 0.93% |

At the end of the session you will receive your total US dollar payoff in cash. The conversion rates have been set so that each subject receives a payment of approximately US$400, regardless of role. The actual payment will be more or less than US$400 depending on the bids of the bidders in the auctions.

## 3. Sequential First-Price Sealed-Bid Auction: Instructions to Bidders (Asymmetric distributions)

Welcome to the Applicant Auction Experiment. In this experiment, you will participate in domain auctions as a bidder. The precise rules and procedures that govern the auctions are explained below.

Various foundations have provided funds for this research. The instructions are simple, and if you follow them carefully and make good decisions you can finish the experiment with a considerable amount of money, which will be paid to you in cash at the end of the experiment. Participants completing the session do not risk losing any money. The experiment will last about four hours.

Currency used in this experiment is Experimental Dollars (ED) in thousands. Throughout the experiment the dollar figures refer to this currency with “thousands” suppressed. At the end of the experiment your earnings will be converted into US Dollars using the conversion rates given below. You will be paid in cash at the end of the experiment. The more ED you earn, the more US Dollars you earn.

## Auction setting

You are a bidder in four domain auctions that will be conducted in this experiment. In each auction, there are 16 bidders competing for 87 domains. Each bidder will be assigned: (i) a set of domains that the bidder has applied for, and (ii) their *private values* for these domains.

Bidders differ in the set of domains that they applied for and have different values for the same domains. The domains for each bidder are shown in the bidding tool discussed at the end of this instruction. Bidders cannot bid for domains they did not apply for.

In the experiment about eight bidders are played by human bidders, while the remaining bidders are played by computer bidders. You will be randomly assigned to one of the human bidders. The computer bidders follow an equilibrium bidding strategy for a simplified setting, as described below.

## Values

Two auctions are conducted in this session. Both auctions are identical in structure, although the values are independent.

Each bidder's value for each domain is randomly and independently drawn from a *triangle distribution* on the interval [0, 5000], rounded to the nearest integer. These values are private—each bidder will know only her own value. Two types of triangle distributions are used depending on whether the bidder is *strong* or *weak*. There are three strong bidders: Donuts, Google and Amazon. The rest of the bidders are weak.

- The value, *v*, of a *strong bidder* for each domain is randomly and independently drawn from a distribution with density $f_s\left(v\right)=2\frac{v}{\bar{v}^2}$, and cumulative $F_s\left(v\right)=\left(\frac{v}{\bar{v}}\right)^2$ on the interval [0, 5000], rounded to the nearest integer. The mean value then is 3750 thousand dollars.
- The value *v* of a *weak bidder* for each domain is randomly drawn from a distribution with density $f_w\left(v\right)=\frac{2}{\bar{v}}\left(1-\frac{v}{\bar{v}}\right)$, , and cumulative $F_w\left(v\right)=1-(1-\frac{v}{\bar{v}})^2$ on the interval [0, 5000], rounded to the nearest integer. The mean value then is 1250 thousand dollars.

## Auction rules

A Sequential First-Price Sealed-Bid Auction will be used throughout this session. All 87 domains will be sold in a sequence of first-price sealed-bid rounds. In each round, a small batch of domains will be auctioned simultaneously using the first-price sealed-bid format: for each domain, the high bidder wins and pays her bid. The winner's payment is split equally among the losing bidders. Ties are broken randomly.

The batching of domains, as well as the auction schedule for each round will be announced before the first round takes place.

You will be able to make bids on each of the domains you applied for. At the time you place your bid you will know the set of domains you applied for (and therefore can bid on) and the set of domains each of the other bidders applied for. Thus, you will know both the number of bidders and the other companies that applied for each domain. If you fail to place a bid in the time available—either before or during the round in which the particular domain is auctioned—a bid of zero is assumed.

After a round has ended, the winning bid amount will be disclosed, but not the identity of the winner.

## Profits

A bidder's total profit is the sum of the profits from all domains of interest. Due to the payment rule in this auction, along with the usual profit from the domains you have won, you also profit from the domains that you have lost.

- Profit from domain won:

$$\text{Profit}_{won} = \text{ value} - \text{price}$$

- Profit from domain lost, where *n* is the initial number of bidders for the domain:

$$\text{Profit}_{lost} = \frac{\text{winner's payment}}{\text{n} - 1}$$

### *Examples*

Suppose that your valuation for the domain is 4,500 and you win it at a price of 4,000. Then your profit from this domain is equal to 4,500 – 4,000 = 500 ED.

Suppose that you lose the domain, the initial number of bidders for that domain is 5, and the winner pays 4,000. Then your profit from this domain is equal to 4,000 / 4 = 1,000 ED.

## Deposit

Each bidder has an initial deposit. The size of the deposit determines the maximum bidding commitment the bidder can make. The total of active bids and winning payments cannot exceed five times the current deposit. As domains are sold, the payment received by the loser is added to the deposit amount.

The auction system will prevent a bidder from placing bids on a collection of domains that would cause the bidder's total commitment to exceed five times the bidder's current deposit.

## Bidding strategy

The sequential first-price sealed-bid auction allows the bidders to adopt complex bidding strategies. Below are some results from auction theory about single-item auctions that may be relevant when devising your bidding strategy.

Before stating the results, here is some notation. There are $n$ bidders with bidder $i$ assigning a value of $V_i$ to the object. Each $V_i$ is drawn independently on the interval $[0, \bar{v}]$ according to the cumulative distribution function $F_i$ with a positive density $f_i$. ( $\bar{v} = 5000$ in the experiment.)

Recall that in the standard private-value setting where winning payments are retained by the auctioneer, the first-price auction has a unique symmetric equilibrium when each bidder's value is drawn from the same distribution *F* with positive density *f*. It is

$$b(v) = \mathrm{v} - \mathrm{F(v)}^{-(\mathrm{n}-1)} \int_0^{\mathrm{v}} \mathrm{F(u)}^{\mathrm{n}-1} \mathrm{du}.$$

For the uniform distribution on the interval $[0,\bar{v}]$, this reduces to $b(v) = \frac{n-1}{n}v$. Thus with two bidders you bid one-half of your value.

Bidder incentives change in our setting where the winner's payment is shared equally among the losers. Notice that losing is made more attractive in this case, relative to the standard auction—the loser receives a share of the winner's payment, rather than 0.

We can calculate the unique symmetric equilibrium when there are two bidders and each bidder's value is independently drawn from a triangle distribution.

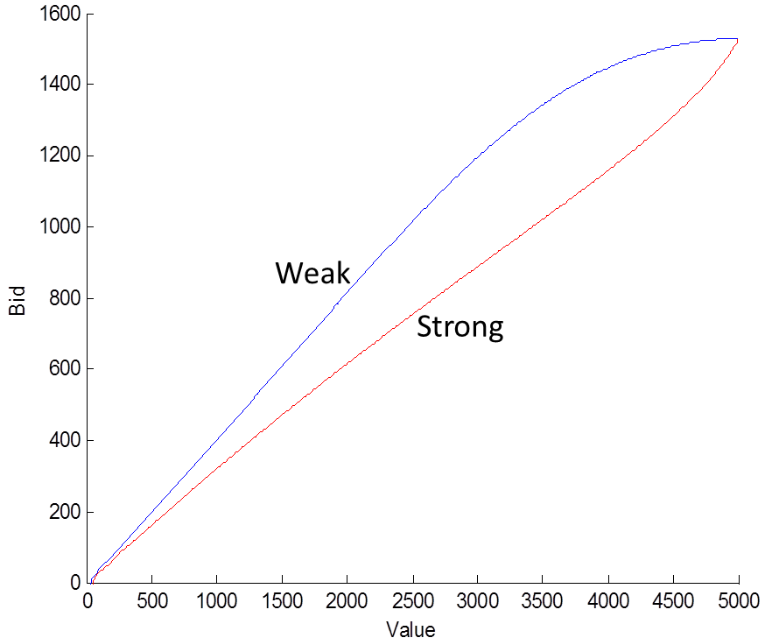
With two strong bidders, the symmetric equilibrium bid function is

$$b_{2strong}(v) = \frac{2v}{5}.$$

With two weak bidders, the symmetric equilibrium bid function is

$$b_{2weak}(v) = \frac{v(40 + 3\frac{v}{\bar{v}}(4\frac{v}{\bar{v}} - 15))}{30(\frac{v}{\bar{v}} - 2)^2}.$$

When the bidders' values are drawn from different distributions then numerical methods must be used to compute the equilibrium. As an example, we present the case with one strong bidder and one weak bidder in the figure below. Notice that the weak bidder bids more aggressively than the strong bidder to compensate for the weakness; similarly the strong bidder bids less aggressively than the weak bidder in recognition of her relative strength.



## Bidding tool

In addition to the auction system, you will have a bidding tool:

bidding-tool-sequential-asymmetric-25oct5pm-xy-role.xlsm.

*Please make a copy of this file and change the name of this tool before you paste your values. In particular, (1) replace "xy" with either an "X" or a "Y" depending on whether you have an X or Y in the URL with your login instructions, and (2) replace "role" with your company name, e.g. Google. Then go to the auction system and copy and paste your values. You may do this in advance of the experiment but be sure to bring you customized file to the lab.*

All bidders have the same tool. The tool allows you to explore alternative bidding strategies. It includes all the information that is common knowledge: the domains, the bidders and which domains each can bid for, the equilibrium bid functions wherever the equilibrium is known (as described above). Note that there is a separate sheet for each auction. Be sure you are using the correct sheet for the particular auction.

To use the tool, you will need to go to the appropriate sheet. Each of the two auctions has a separate sheet—Asymmetric1 and Asymmetric2. Then sort the sheet by your bidder name and then by domain, so that all the domains you can bid for are listed first and in alphabetical order. Then you can paste your values into the sheet from the auction system by clicking on the Bidder Info button, selecting all domains and values in the window toward the bottom of the screen, then Ctrl-C to copy. Of course this step must be repeated for each auction. Be sure to save the Workbook once your values are pasted in. Also save your workbook at the end of each auction.

You can then use the tool to explore various bidding strategies. *You may do this in advance of the experimental session.* Once you are happy with your bids, you can enter them directly in the auction system, or if you have many bids, you can upload your bids. To upload bids, you must first create a bid upload file in .csv format. Then go to the auction system and click the Upload button on the Bidding screen to upload the bids. Be sure to check your uploaded bids carefully. Any errors can be corrected directly or through another upload.

Please note that you initially may not have sufficient money on deposit to bid as high as you would like on all of your domains. You may need to limit some bids early on in order to satisfy the limitation on bids coming from your limited deposit. You commitments from active bids and domains won can be at most five times your current deposit.

### Payment conversion

Your profits in each auction in ED currency is converted to the US Dollars by the formula

$$\text{Payment in US dollars} = \text{Profit in ED} \times \text{rate for role}$$

The payout rate for each role is given below:

| | **Rate** |
|---|---|
| **Bidder** | **Asymmetric** |
| Donuts | 0.10% |
| Minds+Machine | 0.34% |
| Google | 0.26% |
| Famous Four | 0.34% |
| Uniregistry | 0.32% |
| Afilias | 1.04% |
| Amazon | 0.36% |
| Radix | 1.10% |

At the end of the session you will receive your total US dollar payoff in cash. The conversion rates have been set so that each subject receives a payment of approximately US$400, regardless of role. The actual payment will be more or less than US$400 depending on the bids of the bidders in the auctions.

## 4. Simultaneous Ascending Clock Auction: Instructions to Bidders (Asymmetric distributions)

Welcome to the Applicant Auction Experiment. In this experiment, you will participate in domain auctions as a bidder. The precise rules and procedures that govern the auctions are explained below.

Various foundations have provided funds for this research. The instructions are simple, and if you follow them carefully and make good decisions you can finish the experiment with a considerable amount of money, which will be paid to you in cash at the end of the experiment. Participants completing the session do not risk losing any money. The experiment will last about four hours.

Currency used in this experiment is Experimental Dollars (ED) in thousands. Throughout the experiment the dollar figures refer to this currency with “thousands” suppressed. At the end of the experiment your earnings will be converted into US Dollars using the conversion rates given below. You will be paid in cash at the end of the experiment. The more ED you earn, the more US Dollars you earn.

## Auction setting

You are a bidder in four domain auctions that will be conducted in this experiment. In each auction, there are 16 bidders competing for 87 domains. Each bidder will be assigned: (i) a set of domains that the bidder has applied for, and (ii) their *private values* for these domains.

Bidders differ in the set of domains that they applied for and have different values for the same domains. The domains for each bidder are shown in the bidding tool discussed at the end of this instruction. Bidders cannot bid for domains they did not apply for.

In the experiment about eight bidders are played by human bidders, while the remaining bidders are played by computer bidders. You will be randomly assigned to one of the human bidders. The computer bidders follow an equilibrium bidding strategy for a simplified setting, as described below.

## Values

Two auctions are conducted in this session. Both auctions are identical in structure, although the values are independent.

Each bidder’s value for each domain is randomly and independently drawn from a *triangle distribution* on the interval [0, 5000], rounded to the nearest integer. These values are private—each bidder will know only her own value. Two types of triangle distributions are used depending on whether the bidder is *strong* or *weak*. There are three strong bidders: Donuts, Google and Amazon. The rest of the bidders are weak.

- The value, *v*, of a *strong bidder* for each domain is randomly and independently drawn from a distribution with density $f_s(v) = 2\frac{v}{\bar{v}^2}$, and cumulative $F_s(v) = \left(\frac{v}{\bar{v}}\right)^2$ on the interval [0, 5000], rounded to the nearest integer. The mean value then is 3750 thousand dollars.
- The value *v* of a *weak bidder* for each domain is randomly drawn from a distribution with density $f_w(v) = \frac{2}{\bar{v}}\left(1 - \frac{v}{\bar{v}}\right)$, , and cumulative $F_w(v) = 1 - (1 - \frac{v}{\bar{v}})^2$ on the interval [0, 5000], rounded to the nearest integer. The mean value then is 1250 thousand dollars.

## Auction rules

A Simultaneous Ascending Clock Auction will be used throughout this session.

All 87 domains will be sold simultaneously in multiple rounds. In each round, for each domain, the number of active bidders is announced together with two prices: (i) the *minimum price to bid,* and (ii) the *minimum price to continue*. The *minimum price to bid* is where the auction has reached at the end of the last round (or \$0 in the first round). You are already committed to a bid of at least this amount, which is why this is the lowest bid you may place. The *minimum price to continue* is the smallest bid that you may place in the current round in order to be given the opportunity to bid in the next round. Thus, for each domain of interest, the submitted bid indicates your decision to either exit in the current round with a bid that is between the *minimum price to bid* and the *minimum price to continue*, or continue with a bid that is at or above the *minimum bid to continue*, in which case you will be given the opportunity to continue bidding on the domain in the next round. In other words you may:

- *Exit* from a domain by choosing a bid that is less than the announced *minimum price to continue* for that round. A bidder cannot bid for a domain for which she has submitted an exit bid.
- You may *continue* to bid on a domain of interest by choosing a bid that is greater than or equal to the announced *minimum price to continue* for that round.

At the end of the round, the auction system will identify if the domain received multiple bids that are greater than or equal to the *minimum price to continue*. If so, the auction for that domain will proceed to the next round. The price for the domain will be increased by a percentage increment in the next round.

If there is only one or no bid that is greater than or equal to the *minimum price to continue* for a domain, the domain is won by the highest bidder. Ties are broken randomly.

The auction continues until there is no domain for which multiple bidders are active; that is, there is no excess demand, since all or all-but-one bidder has placed an exit bid for the domain at a price less than the *minimum price to continue*.

Pricing is based on a second-price rule: Each domain then is awarded to the highest bidder, who will pay the highest losing bid. Each losing bidder will receive an equal share of the winner's payment; that is, each loser receives the winner's payment divided by the number of losing bidders for the particular domain.

In each round, bidders need to submit their bids within the time allowed. If no action is taken for a domain, it will be assumed that the bidder has chosen to exit from that domain.

## Profits

A bidder's total profit is the sum of the profits from all domains of interest. Due to the payment rule in this auction, along with the usual profit from the domains you have won, you also profit from the domains that you have lost.

- Profit from domain won:

$$\text{Profit}_{won} = \text{value} - \text{price}$$

- Profit from domain lost, where *n* is the initial number of bidders for the domain:

$$\text{Profit}_{lost} = \frac{\text{winner's payment}}{\text{n} - 1}$$

### *Examples*

Suppose that your valuation for the domain is 4,500 and you win it at a price of 4,000. Then your profit from this domain is equal to 4,500 – 4,000 = 500 ED.

Suppose that you lose the domain, the initial number of bidders for that domain is 5, and the winner pays 4,000. Then your profit from this domain is equal to 4,000 / 4 = 1,000 ED.

## Deposit

Each bidder has an initial deposit. The size of the deposit determines the maximum bidding commitment the bidder can make. The total of active bids and winning payments cannot exceed five times the current deposit. As domains are sold, the payment received by the loser is added to the deposit amount. Also for domains that have not yet sold but for which the bidder has exited, the bidder's deposit is credited with the minimum payment that the bidder may receive once the domain is sold—this is the *minimum price to bid* in the current round.

The auction system will prevent a bidder from placing bids on a collection of domains that would cause the bidder's total commitment to exceed five times the bidder's current deposit.

## Bidding strategy

The simultaneous ascending clock auction allows the bidders to adopt complex bidding strategies. Below are some results from auction theory about single-item auctions that may be relevant when devising your bidding strategy.

Before stating the results, here is some notation. There are $n$ bidders with bidder $i$ assigning a value of $V_i$ to the object. Each $V_i$ is drawn independently on the interval $[0, \bar{v}]$ according to the cumulative distribution function $F_i$ with a positive density $f_i$. ( $\bar{v} = 5000$ in the experiment.)

Recall that in the standard private-value setting where winning payments are retained by the auctioneer, the second-price and ascending clock auctions both have the same dominant strategy equilibrium: bid (up to) your private value, or $b(v) = v$.

Bidder incentives change in our setting where the winner's payment is shared equally among the losers. Notice that losing is made more attractive in this case, relative to the standard auction—the loser receives a share of the winner's payment, rather than 0.

We can calculate the unique symmetric equilibrium when there are two bidders and each bidder's value is independently drawn from a triangle distribution.

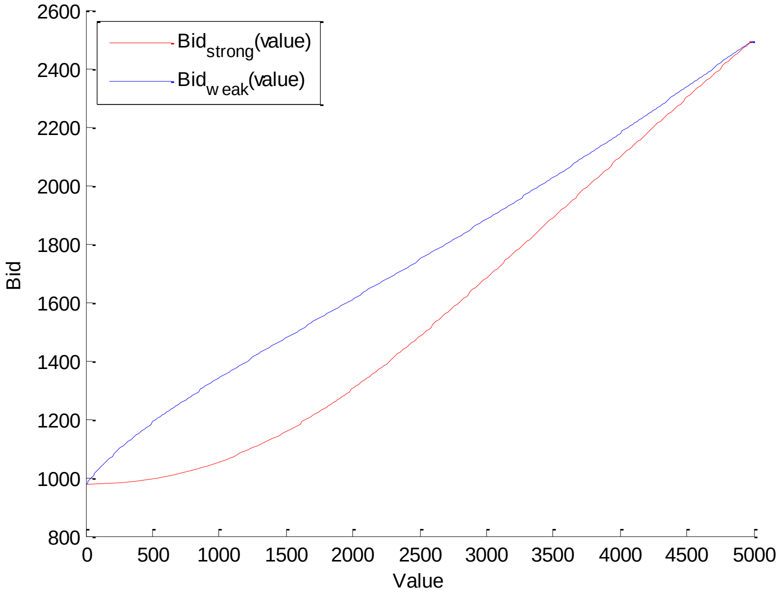
With two strong bidders, the symmetric equilibrium bid function is

$$b_{2strong}(v) = \bar{v}\,\frac{4 + 2\frac{v}{\bar{v}}\left(4 + 3\frac{v}{\bar{v}}\left(2 + \frac{v}{\bar{v}}\right)\right)}{15\left(1 + \frac{v}{\bar{v}}\right)^2}.$$

With two weak bidders, the symmetric equilibrium bid function is

$$b_{2weak}(v) = \frac{\bar{v}}{10}(1 + 4\frac{v}{\bar{v}}).$$

When the bidders' values are drawn from different distributions then numerical methods must be used to compute the equilibrium. As an example, we present the case with one strong bidder and one weak bidder in the figure below. Notice that the weak bidder bids more aggressively than the strong bidder to compensate for the weakness; similarly the strong bidder bids less aggressively than the weak bidder in recognition of her relative strength.



## Bidding tool

In addition to the auction system, you will have a bidding tool:

bidding-tool-simultaneous-asymmetric-24oct5pm-xy-role.xlsm.

*Please make a copy of this file and change the name of this tool before you paste your values. In particular, (1) replace "xy" with either an "X" or a "Y" depending on whether you have an X or Y in the URL with your login instructions, and (2) replace "role" with your company name, e.g. Google. Then go to the auction system and copy and paste your values. You may do this in advance of the experiment but be sure to bring you customized file to the lab.*

All bidders have the same tool. The tool allows you to explore alternative bidding strategies. It includes all the information that is common knowledge: the domains, the bidders and which domains each can bid for, the equilibrium bid functions wherever the equilibrium is known (as described above). Note that there is a separate sheet for each auction. Be sure you are using the correct sheet for the particular auction.

To use the tool, you will need to go to the appropriate sheet. Each of the two auctions has a separate sheet—Asymmetric1 and Asymmetric2. Then sort the sheet by your bidder name and then by domain, so that all the domains you can bid for are listed first and in alphabetical order. Then you can paste your values into the sheet from the auction system by clicking on the Bidder Info button, selecting all domains and values in the window toward the bottom of the screen, then Ctrl-C to copy. Of course this step must be repeated for each auction. Be sure to save the Workbook once your values are pasted in. Also save your workbook at the end of each auction.

You can then use the tool to explore various bidding strategies. *You may do this in advance of the experimental session.* Once you are happy with your bids, you can enter them directly in the auction system, or if you have many bids, you can upload your bids. To upload bids, you must first create a bid upload file in .csv format. Then go to the auction system and click the Upload button on the Bidding screen to upload the bids. Be sure to check your uploaded bids carefully. Any errors can be corrected directly or through another upload.

Please note that you initially may not have sufficient money on deposit to bid as high as you would like on all of your domains. You may need to limit some bids early on in order to satisfy the limitation on bids coming from your limited deposit. You commitments from active bids and domains won can be at most five times your current deposit.

## Payment conversion

Your profits in each auction in ED currency is converted to the US Dollars by the formula

$$\text{Payment in US dollars} = \text{Profit in ED} \times \text{rate for role}$$

The payout rate for each role is given below:

| | **Rate** |
|---|---|
| **Bidder** | **Asymmetric** |
| Donuts | 0.10% |
| Minds+Machine | 0.36% |
| Google | 0.26% |
| Famous Four | 0.38% |
| Uniregistry | 0.36% |
| Afilias | 1.28% |
| Amazon | 0.36% |
| Radix | 1.20% |

At the end of the session you will receive your total US dollar payoff in cash. The conversion rates have been set so that each subject receives a payment of approximately US$400, regardless of role. The actual payment will be more or less than US$400 depending on the bids of the bidders in the auctions.

EXHIBIT PC-5

Exhibit PC-5

*Handbook of Telecommunications Economics*, Martin Cave, Sumit Majumdar, and Ingo Vogelsang, eds.,
Amsterdam: Elsevier Science B.V., Chapter 14, 605-639, 2002.

# Spectrum Auctions

Peter Cramton*

University of Maryland

February 2001

*Abstract*

Auctions have emerged as the primary means of assigning spectrum licenses to companies wishing to provide wireless communication services. Since July 1994, the Federal Communications Commission (FCC) has conducted 33 spectrum auctions, assigning thousands of licenses to hundreds of firms. Countries throughout the world are conducting similar auctions. I review the current state of spectrum auctions. Both the design and performance of these auctions are addressed.

*JEL No.*: D44 (Auctions), L96 (Telecommunications)
*Keywords*: Auctions, Multiple-Item Auctions, Spectrum Auctions, Telecommunications

Send comments to:

Professor Peter Cramton
Department of Economics
University of Maryland
College Park, MD 20742-7211

cramton@umd.edu
301.405.6987

*I am grateful to the National Science Foundation for funding. I advised several governments on auction design and several bidders on auction strategy. The views expressed are my own.

# Spectrum Auctions

Peter Cramton

From July 1994 to February 2001, the Federal Communications Commission (FCC) conducted 33 spectrum auctions, raising over $40 billion for the U.S. Treasury. The auctions assigned thousands of licenses to hundreds of firms. These firms are now in the process of creating the next generation of wireless communication services. The FCC is not alone. Countries throughout the world now are using auctions to assign spectrum. Indeed, the early auctions in Europe for third-generation (3G) mobile wireless licenses raised nearly $100 billion. Auctions have become the preferred method of assigning spectrum.

The FCC auctions have shown that using an auction to allocate scarce resources is far superior to the prior methods: comparative hearings and lotteries. With a well-designed auction, there is a strong tendency for the licenses to go to the parties that value them the most, and the Treasury obtains much-needed revenues in the process.

Overall, the auctions have been a tremendous success, putting essential spectrum in the hands of those best able to use it. The auctions have fostered innovation and competition in wireless communication services. Taxpayers, companies, and especially consumers have benefited from the auctions. In comparison with other countries, the FCC auctions represent the state-of-the-art in spectrum auction design and implementation. The FCC began its auctions with an innovative design, and has continued to improve the auctions since then. The FCC’s leadership in spectrum auctions has had positive consequences worldwide. Many countries wisely have imitated the FCC auctions; those that have not have suffered from inefficient license assignments and other flaws.

All but two of the FCC auctions have used a simultaneous ascending design in which groups of related licenses are auctioned simultaneously over many rounds of bidding. In each round, bidders submit new higher bids on any of the licenses they desire, bumping the standing high bidder. The auction ends when a round passes without any bidding; that is, no bidder is willing to raise the price on any license. This design is a natural extension of the English auction to multiple related goods. Its advantage over a sequence of English auctions is that it gives the bidders more flexibility in moving among licenses as prices change. As one license gets bid up, a bidder can shift to an alternative that represents a better value. In this way, bidders are able to arbitrage across substitutable licenses. Moreover, they can build packages of complementary licenses using the information revealed in the process of bidding.

There is now substantial evidence that this auction design has been successful. Revenues often have exceeded industry and government estimates. The simultaneous ascending auction may be partially responsible for the large revenues. By revealing information in the auction process, bidder uncertainty is reduced, and the bidders safely can bid more aggressively. Also, revenues may increase to the extent the design enables bidders to piece together more efficient packages of licenses.

Despite the general success, the FCC auctions have experienced a few problems from which one can draw important lessons. One basic problem is the simultaneous ascending auction's vulnerability to revenue-reducing strategies in situations where competition is weak. Bidders have an incentive to reduce their demands in order to keep prices low, and to use bid signaling strategies to coordinate on a split of the licenses. I identify problems with the FCC and other spectrum auctions, and discuss how to minimize these problems.

I begin by explaining why it makes sense to auction the spectrum. Then I discuss auction design. The simultaneous ascending auction is discussed in detail, and its performance is evaluated. I describe how the auction format has evolved in response to perceived problems. The FCC's recently proposed approach to package bidding is discussed. I examine the UMTS auctions in Europe. Finally, I provide advice to governments engaged in spectrum auctions.

## 1 Why auction the spectrum?

There is substantial agreement among economists that auctions are the best way to assign scarce spectrum resources (McMillan 1995). Auctions ask an answer to the basic question 'Who should get the licenses and at what prices?' Ronald Coase (1959) proposed auctioning spectrum over forty years ago, yet it was not until 1994 that spectrum auctions became a reality in the US. Hazlett (1998) provides an analysis of the history that ultimately led to spectrum auctions.

Alternatives to auctions are an administrative process or lotteries. Both alternatives were used and then rejected in the US.

An administrative process has those that are interested in the spectrum make a proposal for how they intend to use it. This approach commonly is referred to as a "beauty contest." After hearing all the proposals, the regulator awards spectrum to those with the most attractive proposals. Beauty contests suffer from several problems. First, they are extremely slow and wasteful. Even with streamlined hearings, it took the FCC an average of two years to award thirty cellular licenses. Competitors spend vast sums trying to influence the regulator's decision. Second, beauty contests lack transparency. It is difficult to see why one proposal won out over another. Worse yet, the ability of the regulator to successfully identify the best proposals is limited.

Unacceptable delays in assigning cellular licenses led the FCC to switch to lotteries. With a lottery, the FCC randomly selects license winners from among those that apply. The problem here is that since the licenses are enormously valuable there is a strong incentive for large numbers to apply. Indeed, the FCC received over four hundred thousand applications for its cellular lotteries. The huge number of applications wasted resources in creating and processing the applications. Moreover, the winners were not those best suited to provide a service. It took years for the licenses to be transferred via private market transactions to those capable of building out a service. Lotteries were quickly abandoned in favor of auctions.

The primary advantage of an auction is its tendency to assign the spectrum to those best able to use it. This is accomplished by competition among license applicants. Those companies with the highest value for the spectrum likely are willing to bid higher than the others, and hence tend to win the licenses. There are several subtleties, which are addressed below that limit the efficiency of spectrum auctions. Still a well-designed auction is apt to be highly efficient. A second important advantage of auctions is that the competition is not wasteful. The competition leads to auction revenues, which can be used to offset distortionary taxation. Finally, an auction is a transparent means of assigning licenses. All parties can see who won the auction and why.

Despite their virtues, standard auctions at best ensure that the bidder with the highest private value wins, rather than the bidder with the highest social value. Private and social values can diverge in these auctions because the winners will be competing in a marketplace. One collection of winners may lead to a more collusive industry structure. For example, a license may be worth more to an incumbent than a new entrant, simply because of the greater market power the incumbent would enjoy without the new entrant. Recognizing this, the regulator typically limits the amount of spectrum any one firm can hold in any geographic area.

## 2 Auction design

Spectrum auctions typically involve the sale of multiple interrelated licenses. We have only begun to understand such auctions in theory and practice. We neither have strong theoretical nor empirical results to guide the design of spectrum auctions. Designing spectrum auctions is as much art as it is science.

The objective of most spectrum auctions is two-fold. The primary goal is efficiency—getting the spectrum in the hands of those best able to use it. A secondary goal is revenue maximization. Even efficiency-minded governments should care about the revenues raised at auction, since auction revenues are less distortionary than the principal source of government revenues—taxation. Economists estimate that the welfare loss from increasing taxes in the United States is in the range of 17–56 cents per dollar of extra revenue raised (Ballard et al. 1985). Hence, in designing the auction, the government should care about revenues. Another common objective is increasing competition for wireless services.

Sometimes it is argued that efficiency is not an important objective. If resale is allowed, will not postauction transactions fix any assignment inefficiencies? The answer is “yes” in a Coasean world without transaction costs. However, transaction costs are not zero. Postauction transactions often are made difficult by strategic behavior between parties with private information and market power. Efficient auctions are possible before assignments are made but may become impossible after an initial assignment. The problem is that the license holder exercises its substantial market power in the resale of the license (Cramton et al. 1987). For this reason, it is important to get the assignment right the first time. Moreover, efficient auctions tend to raise substantial revenues, especially when resale is possible (Ausubel and Cramton 1999).

Much of the research on spectrum auction design has focused on the Personal Communication Services (PCS) auctions in the US. Below I summarize several of the important issues, and the FCC’s ultimate conclusion. These issues are discussed in several papers (e.g., Cramton 1997, McMillan 1994, Milgrom 2000, and Chakravorti et al. 1997, Krishna and Rosenthal 1997, Rosenthal and Wang 1997).

### 2.1 Open bidding is better than a single sealed bid

An essential advantage of open bidding is that the bidding process reveals information about valuations. This information promotes the efficient assignment of licenses, since bidders can condition their bids on more information. Moreover, to the extent that bidder values are affiliated, it may raise auction revenues (Milgrom and Weber 1982), since the winner's curse is reduced. Bidders are able to bid more aggressively in an open auction, since they have better information about the item's value.

The advantage of a sealed-bid design is that it is less susceptible to collusion (Milgrom 1987). Open bidding allows bidders to signal through their bids and establish tacit agreements. With open bidding, these tacit agreements can be enforced, since a bidder can immediately punish another that has deviated from the collusive agreement. Signaling and punishments are not possible with a single sealed bid.

A second advantage of sealed bidding is that it may yield higher revenues when there are ex ante differences among the bidders (Maskin and Riley 1995, Klemperer 1998). This is especially the case if the bidders are risk averse (Maskin and Riley 1984, Matthews 1983). In a sealed bid auction, a strong bidder can guarantee victory only by placing a very high bid. In an open auction, the strong bidder never needs to bid higher than the second-highest value.

In the PCS spectrum auctions, there was a consensus among experts in favor of open bidding. The advantage of revealing more information in the bidding process was thought to outweigh any increased risk of collusion. Collusion was viewed as unlikely, and revenue maximization was a secondary goal.

### *2.2 Simultaneous open bidding is better than sequential auctions*

A frequent source of debate was whether licenses should be sold in sequence or simultaneously. A disadvantage of sequential auctions is that they limit information available to bidders and limit how the bidders can respond to information. With sequential auctions, bidders must guess what prices will be in future auctions when determining bids in the current auction. Incorrect guesses may result in an inefficient assignment when license values are interdependent. A sequential auction also eliminates many strategies. A bidder cannot switch back to an earlier license if prices go too high in a later auction. Bidders are likely to regret having purchased early at high prices, or not having purchased early at low prices. The guesswork about future auction outcomes makes strategies in sequential auctions complex, and the outcomes less efficient.

In a simultaneous auction, a large collection of related licenses is up for auction at the same time. Hence, the bidders get information about prices on all the licenses as the auction proceeds. Bidders can switch among licenses based on this information. Hence, there is less of a need to anticipate where prices are likely to go. Moreover, the auction generates market prices. Similar items sell for similar prices. Bidders do not regret having bought too early or too late.

The Swiss wireless-local-loop auction conducted in March 2000 illustrates the difficulties of sequential sale. Three nationwide licenses were sold in a sequence of ascending auctions. The first two licenses were for a 28 MHz block; the third was twice as big (56 MHz). Interestingly, the first license sold for 121 million francs, the second for 134 million francs, and the third (the large license) sold for 55 million francs. The largest license sold for just a fraction of the prices of the earlier licenses.

Proponents of sequential auctions argue that the relevant information for the bidders is the final prices and assignments. They argue that simultaneous auctions do not reveal final outcomes until the auction is over. In contrast, the sequential auction gives final information about prices and assignments for all prior auctions. This final information may be more useful to bidders than the preliminary information revealed in a simultaneous auction.

Supporters of sequential auctions also point out that the great flexibility of a simultaneous auction makes it more susceptible to collusive strategies. Since nothing is assigned until the end in a simultaneous auction, bidders can punish aggressive bidding by raising the bids on those licenses desired by the aggressive bidder. In a sequential auction, collusion is more difficult. A bidder that is supposed to win a later license at a low price is vulnerable to competition from another that won an earlier license at a low price. The early winner no longer has an incentive to hold back in the later auctions.

In the end, the decision makers at the FCC were convinced that the virtues of the simultaneous auction—greater information release and greater bidder flexibility in responding to information—would improve efficiency. Although the FCC was concerned that a simultaneous auction might be more collusive, it felt that the setting was otherwise not conducive to collusion. In any event, sequential auctions would not eliminate the possibility for collusion.

The ability to successfully implement a novel auction form was a chief concern. However, the FCC was able to test and refine the simultaneous auction in the simpler and lower stake setting of narrowband licenses. In addition, experimental tests of the design were conducted before the first narrowband auction began. Tests were conducted at CalTech's experimental lab by Charles Plott, David Porter, and John Ledyard. Several large bidders conducted their own tests as well. These tests provided evidence that the design would work in practice.

### 2.3 Package bids are too complex

A bidder's value of a license may depend on what other licenses it wins. Philadelphia may be worth more to a bidder if it wins the adjacent licenses in New York and Washington. Hence, bidders may value being able to bid on a combination of licenses, rather than having to place a number of individual bids. With a package bid, the bidder either gets the entire combination or nothing. There is no possibility that the bidder will end up winning just some of what it needs.

With individual bids, bidding for a synergistic combination is risky. The bidder may fail to acquire key pieces of the desired combination, but pay prices based on the synergistic gain. Alternatively, the bidder may be forced to bid beyond its valuation in order to secure the synergies and reduce its loss from being stuck with the dogs. This is the exposure problem. Individual bidding exposes bidders seeking synergistic combinations to aggregation risk.

Not allowing package bids can create inefficiencies. For example, suppose there are two bidders for two adjacent parking spaces. One bidder with a car and a trailer requires both spaces. She values the two spots together at $100 and a single spot is worth nothing; the spots are perfect complements. The second bidder has a car, but no trailer. Either spot is worth \$75, as is the combination; the spots are perfect substitutes. Note that the efficient outcome is for the first bidder to get both spots for a social gain of \$100, rather than \$75 if the second bidder gets a spot. Yet any attempt by the first bidder to win the spaces is foolhardy. The first bidder would have to pay at least \$150 for the spaces, since the second bidder will bid up to \$75 for either one. Alternatively, if the first bidder drops out early, she will "win" one license, losing an amount equal to her highest bid. The only equilibrium is for the second bidder to win a single spot by placing the minimum bid. The outcome is inefficient, and fails to generate revenue. In contrast if package bids are allowed, then the outcome is efficient. The first bidder wins both licenses with a bid of \$75 for both spots.

This example is extreme to illustrate the exposure problem. The inefficiency involves large bidder-specific complementarities and a lack of competition. In the PCS auctions and most other spectrum auctions, the complementarities are less extreme and the competition is greater.

Unfortunately, allowing package bids creates other problems. Package bids may favor bidders seeking large aggregations due to a variant of the free-rider problem, called the threshold problem (Bykowsky, et al. 2000, Milgrom 2000). Continuing with the last example, suppose that there is a third bidder who values either spot at \$40. Then the efficient outcome is for the individual bidders to win both spots for a social gain of 75 + 40 = \$115. But this outcome may not occur when values are privately known. Suppose that the second and third bidders have placed individual bids of \$35 on the two licenses, but these bids are topped by a package bid of \$90 from the first bidder. Each bidder hopes that the other will bid higher to top the package bid. The second bidder has an incentive to understate his willingness to push the bidding higher. He may refrain from bidding, counting on the third bidder to break the threshold of \$90. Since the third bidder cannot come through, the auction ends with the first bidder winning both spaces for \$90.

A second problem with allowing package bids is complexity. If all combinations are allowed, even identifying the revenue maximizing assignment is an intractable integer programming problem when there are many bidders and licenses. The problem can be made tractable by restricting the set of allowable combinations (Rothkopf, et al. 1998). However, these restrictions may eliminate many desirable combinations, especially in broadband PCS where cellular holdings and other existing infrastructure tend to create idiosyncratic license synergies. Alternatively, a bid mechanism can be used that puts the computational burden on the bidders. In the AUSM system, bidders must propose bids that in combination with other bids exceed the amount bid for standing package bids (Banks, et al. 1989).

Increased complexity is a legitimate concern when considering package bids. Although simultaneous auctions with package bids were successfully used in the laboratory (Bykowsky, et al. 2000), it was far from certain that the FCC could successfully run auctions with package bids under the tight time schedule in the early auctions.

The FCC decided against allowing package bids in its early auctions. The threshold problem and increased complexity of package bids were thought to be worse than the exposure problem. However, since the initial PCS auctions, the FCC has done further research on package bidding, and intends to use it in the 700 MHz auction as discussed below.

### *2.4 Other issues*

Having settled on a simultaneous ascending auction without package bids, several issues of implementation remained.

How much information should the bidders be given? The insights from Milgrom and Weber (1982) suggest that typically more public information is better. Hence, with the exception of bidder identities in the nationwide auction, the FCC decided to reveal all information: the identities of the bidders, all the bids, and the bidders' current eligibility. So long as collusion and predatory bidding are not problems, revealing more information should improve efficiency and increase revenues. It also makes for a more open process.

Should the rounds be discrete or continuous? The FCC decided on discrete rounds, which would give the bidders a specific amount of time to respond to bids. Continuous bidding has the advantage that it makes endogenous the time between bids. Bidders can respond quickly when the strategic situation is simple, and take more time when it is complex. Discrete bidding is easier to implement and it gives the bidders a specific schedule to follow. Bidders know exactly when new information will be available and when they have to respond.

How can the FCC best control the pace of the auction? There are three key instruments: the frequency of rounds, the minimum bid increments, and an activity rule, which sets minimum levels of bidding activity. These are discussed later.

## 3 Simultaneous ascending auction

The simultaneous ascending auction has emerged as the standard approach to spectrum auctions. This design has been successfully used and refined by the FCC in over two-dozen auctions. Other countries, such as Australia, Canada, Mexico, the Netherlands, and the United Kingdom, have used this design as well. Below is a description of the rules for a generic FCC auction.

The simultaneous ascending auction works as follows. A group of licenses with strong value interdependencies are up for auction at one time. A bidder can bid on any collection of licenses in any round, subject to an activity rule which determines the bidder's current eligibility. The auction ends when a round passes with no new bids on any license. This auction form was thought to give the bidders flexibility in expressing values and building license aggregations. An auction winner gains the exclusive right to use the spectrum in accordance with FCC rules for a period of ten years. Licenses typically are renewed with a negligible charge provided the licensee has adhered to FCC rules and met buildout requirements. Licensees at any time may resell licenses purchased without special preference. Resale of licenses purchased with special preference is restricted to prevent “unjust enrichment.”

*Spectrum Cap*. To promote competition, a firm is limited in the quantity of spectrum it can hold in any market. For example in US auctions, firms can hold no more than 45 MHz of broadband spectrum in any area, assuring that there are at least five broadband wireless competitors in each market.

*Payment Rules*. Payments are received by the FCC at three times: (1) An upfront payment before the bidding begins assures that the bidder is serious. Any withdrawal or default penalties are taken from the bidder's upfront payment. (2) A down payment of 20 percent is paid within five business days after the close of the auction. (3) A final payment of the remaining 80 percent is paid within five business days of the award of the license. Licenses are awarded one to three months after the auction.

The upfront payment is a refundable deposit. It is due two weeks before the auction begins and defines the bidder's maximum eligibility in any round of bidding. A bidder interested in winning a large quantity of licenses would have to submit a large upfront payment; a bidder with more limited interests could submit a smaller upfront payment. The size of a license typically is measured in MHz-pop: the bandwidth in megahertz times the population in the license area. In early PCS auctions, each bidder made an upfront payment of \$.02 per MHz-pop for the largest combination of licenses the bidder intended to be active on in any round. A bidder is active on a license if it places a new bid in the round or was the high bidder on the license in the prior round. Thus, an upfront payment of \$6 million in the AB broadband PCS auction would make a bidder eligible to be active on 30 MHz licenses covering $6/(30\times.02) = 10$ million people. The upfront payment is not license specific; it simply limits total bidding activity in any round.

*Designated Entities*. To encourage broad participation in wireless communications, designated firms (women, minorities, and/or small businesses) were given bidding credits on specific licenses. These credits, ranging from 10% to 40%, were intended to offset any disadvantage these firms faced in raising capital and providing services. Some auctions also gave designated entities favorable installment payments terms. These were later abandoned.

*Minimum Bid Increments*. To assure that the auction concludes in a reasonable amount of time, the FCC specifies minimum bid increments between rounds. Bid increments are set at the greater of a percentage increment and an absolute increment. Bid increments are adjusted in response to bidder behavior. In the early rounds, when bid activity is high, the FCC sets larger bid increments; in the later rounds, when bid activity is low, the FCC sets smaller bid increments. Typically, the bid increments are between 5 and 20 percent.

*Activity Rule*. The activity rule, proposed by Paul Milgrom and Robert Wilson, is a further device for controlling the pace of the auction. It forces a bidder to maintain a minimum level of activity to preserve its current eligibility. As the auction progresses, the activity requirement increases in stages. For example, the activity requirement might be 60% in stage 1, 80% in stage 2, and 100% in stage 3 (the final stage). With a 60% activity requirement, each bidder must be active on a quantity of licenses, measured in MHz-pop, equal to at least 60% of the bidder’s current eligibility. If activity falls below the 60% level, then the bidder's current eligibility is reduced to its current activity divided by 60%. With a 100% activity requirement, the bidder must be active on 100% of its current eligibility or its eligibility drops to its current activity. The lower activity requirement early in the auction gives the bidder greater flexibility in shifting among license aggregations early on when there is the most uncertainty about what will be obtainable.

A waiver prevents a reduction in eligibility in the event of bidder error or some other problem. Bidders typically are given five waivers. Waivers are applied automatically. An automatic waiver is used whenever a bidder's eligibility would otherwise fall as a result of its reduced bid activity. A bidder that does not wish to maintain its eligibility from the prior round may override the automatic waiver.

*Number of Rounds per Day*. A final means of controlling the pace of the auction is the number of rounds per day. Typically, fewer rounds per day are conducted early in the auction when the most learning occurs. In the later rounds, there is much less bidding activity, and the rounds can occur more quickly. The FCC has conducted as few as one round per day and as many as twenty per day.

*Stopping Rule*. A simultaneous stopping rule is used to give the bidders maximum flexibility in pursuing backup strategies. All markets close if a single round passes in which no new bids are submitted on any license, and the auction is in its final stage.

*Bid Information*. Each bidder is fully informed about the identities of the bidders, the size of the upfront payments, and which bidders qualify as designated entities. High bids and bidder identities are posted after each round. In addition, all bids and bidder identities are displayed at the conclusion of each round, together with each bidder's eligibility and waivers.

*Bid Withdrawal*. The high bidders can withdraw their bids subject to a bid withdrawal penalty. If a bidder withdraws its high bid, the FCC is listed as the high bidder and the minimum bid is the second-highest bid for that license. The second-highest bidder is in no way responsible for the bid, since this bidder may have moved on to other properties. If no firm bids on the license, the FCC can reduce the minimum bid. Typically, the FCC drops the minimum bid at most once, before committing not to reduce the minimum bid further.

To discourage insincere bidding, there are penalties for withdrawing a high bid. The penalty is the larger of 0 and the difference between the withdrawn bid and the final sale price. This penalty is consistent with the standard remedy for breach of contract. The penalty equals the damage suffered by the FCC as a result of the withdrawal. If the bidder defaults or is disqualified after the close of the auction, the penalty is increased by 3% of the eventual sale price to compensate the FCC for additional selling costs. The additional 3% default payment is also intended to discourage defaults (after the auction closes) relative to withdrawals (during an auction).

## 4 Performance of the simultaneous ascending auction

Since we do not observe the values firms place on licenses, it is impossible to directly assess the efficiency of the simultaneous ascending auction. Nonetheless, we can indirectly evaluate the auction design from the observed behavior (Cramton 1998, McAfee and McMillan 1996). I focus especially on the three PCS broadband auctions, which I refer to as the AB auction, the C auction, and the DEF auction, indicating the block(s) of spectrum that were assigned in each.

Revenue is a first sign of success. Auction revenues have been substantial. Revenues in US auctions typically have exceeded industry and government estimates. The simultaneous ascending auction may be partially responsible for the large revenues. By revealing information in the auction process, the winner's curse is reduced, and the bidders can bid more aggressively. Also, revenues may increase to the extent the design enables bidders to piece together more efficient packages of licenses.

A second indicator of success is that the auctions tended to generate market prices. Similar items sold for similar prices. In the narrowband auctions, the price differences among similar licenses were at most a few percent and often zero. In the first broadband auction, where two licenses were sold in each market, the prices differed by less than one minimum bid increment in 42 of the 48 markets.

A third indicator of success is the formation of efficient license aggregations. Bidders did appear to piece together sensible license aggregations. This is clearest in the narrowband auctions. In the nationwide narrowband auction, bidders buying multiple bands preferred adjacent bands. The adjacency means that the buffer between bands can be used for transmission, thus increasing capacity. The two bidders that won multiple licenses were successful in buying adjacent bands. In the regional narrowband auction, the aggregation problem was more complicated. Several bidders had nationwide interests, and these bidders would have to piece together a license in each of the five regions, preferably all on the same band, in order to achieve a nationwide market. The bidders were remarkably successful in achieving these aggregations. Four of the six bands sold as nationwide aggregations. Bidders were able to win all five regions within the same band. Even in the two bands that were not sold as nationwide aggregations, bidders winning multiple licenses won geographically adjacent licenses within the same band.

Large aggregations were also formed in the PCS broadband auctions. Bidders tended to win the same band when acquiring adjacent licenses. In the AB auction, the three bidders with nationwide interests appeared to have efficient geographic coverage when one includes their cellular holdings. The footprints of smaller bidders also seem consistent with the bidders' existing infrastructures. In the C-block auction, bidders were able to piece together contiguous footprints, although many bidders were interested in stand-alone markets.

Ausubel et al. (1997) and Moreton and Spiller (1998) analyze the AB and C auction data to see if there is evidence of local synergies. Consistent with local synergies, these studies find that bidders did pay more when competing with a bidder holding neighboring licenses. Hence, bidders did bid for synergistic gains and, judging by the final footprints, often obtained them.

The two essential features of the FCC auction design are (1) the use of multiple rounds, rather than a single sealed bid, and (2) simultaneous, rather than sequential sales. The goal of both of these features is to reveal information and then give the bidders the flexibility to respond to the information. There is substantial evidence that the auction was successful in revealing extensive information. Bidders had good information about both prices and assignments at a point in the auction where they had the flexibility to act on the information (Cramton 1997). The probability that a high bidder would eventually win the market was high at the midpoint of each auction. Also the correlation between mid-auction and final prices was high in each auction. Information about prices and assignments improved throughout each auction and was of high quality before bidders lost the flexibility to move to alternative packages.

The absence of resale also suggests that the auctions were highly efficient. In the first two years of the PCS auctions, there was little resale. GTE was the one exception. Shortly after the AB auction ended, GTE sold its AB winnings for about what it paid for the licenses. Apparently there was a shift in corporate strategy away from PCS and toward cellular.

## 5 Demand reduction and collusive bidding

Despite the apparent success of these auctions, an important issue limiting both efficiency and revenues is demand reduction and collusive bidding. This issue stems from the fact that these are multiple-item auctions. The efficiency results from single-item auctions do not carry forward to the multiple-item setting. In an ascending auction for a single item, each bidder has a dominant strategy of bidding up to its private valuation. Hence, the item always goes to the bidder with the highest value. If, instead, two identical items are being sold in a simultaneous ascending auction, then a bidder has an incentive to stop bidding for the second item before its marginal valuation is reached. Continuing to bid for two items raises the price paid for the first. As a result, the bidder with the highest value for the second item may be outbid by a bidder demanding just a single unit.

This logic is quite general. In multi-unit uniform-price auctions, typically every equilibrium is inefficient (Ausubel and Cramton 1996). Bidders have an incentive to shade their bids for multiple units, and the incentive to shade increases with the quantity being demanded. Hence, large bidders will shade more than small bidders. This differential shading creates an inefficiency. The small bidders will tend to inefficiently win licenses that should be won by the large bidders. The intuition for this result is analogous to why a monopolist's marginal revenue curve lies below its demand curve: bringing more items to market reduces the price received on all items. In the auction, demanding more items raises the price paid on all items. Hence, the incentive to reduce demand.

The FCC spectrum auctions can be viewed as an ascending-bid version of a uniform-price auction. Certainly, for licenses that are close substitutes, the simultaneous ascending auction has generated near uniform prices for similar items. However, the incentives for demand reduction and collusive bidding likely are more pronounced in an ascending version of the uniform-price auction (Cramton and Schwartz 1999, Ausubel and Schwartz 1999).[1] To illustrate this, consider a simple example with two identical goods and two risk-neutral bidders. Suppose that to each bidder the marginal value of winning one item is the same as the marginal value of winning a second item. These values are assumed independent and private, with each bidder drawing its marginal value from a uniform distribution on [0, 100]. First

---

[1] But see Perry and Reny (1999) that construct an efficient equilibrium in the simultaneous ascending auction.

consider the sealed-bid uniform price auction where each bidder privately submits two bids and the highest two bids secure units at a per-unit charge equal to the third highest bid. There are two equilibria to this sealed-bid auction: a demand-reducing equilibrium where each bidder submits one bid for $0 and one bid equal to its marginal value; and a sincere equilibrium where each bidder submits two bids equal to its marginal value. The sincere equilibrium is fully efficient in that both units will be awarded to the bidder who values them more. The demand-reducing equilibrium, however, raises zero revenue (the third-highest bid is zero) and is inefficient since the bidder with the higher value wins only one unit.

Next consider the same setting, but where an ascending version of the auction is used. Specifically, view the ascending auction as a two-button auction where there is a price clock that starting from price 0 increases continuously to 100. The bidders depress the buttons to indicate the quantity they are bidding for at every instant. The buttons are “non-repushable” meaning a bidder can decrease its demand but cannot increase its demand. Each bidder observes the price and can observe how many buttons are being depressed by its opponent. The auction ends at the first price such that the total number of buttons depressed is less than or equal to two. This price is called the stop-out price. Each bidder will win the number of units she demands when the auction ends, and is charged the stop-out price for each unit she wins. In this game, if weakly dominated strategies are eliminated, there is a unique equilibrium in which the bidding ends at a price of zero, with both bidders demanding just a single unit. The reason is that each bidder knows that if it unilaterally decreases its bidding to one unit, the other bidder will instantaneously end the auction, as argued above. But since the bidder prefers the payoff from winning one unit at the low price over its expected payoff of winning two units at the price high enough to eliminate the other bidder from the auction, the bidder will immediately bid for just one unit, inducing an *immediate* end to the auction. Thus, the only equilibrium here is analogous to the demand-reducing equilibrium in the sealed-bid uniform-price auction. The efficient equilibrium does not obtain. This example shows that the incentives to reduce demand can be more pronounced in an open auction, where bidders have the opportunity to respond to the elapsed bidding. The 1999 German GSM spectrum auction, which lasted just two rounds, illustrates this behavior (Jehiel and Moldovanu 2000).

This example is meant to illustrate that in simple settings with few goods and few bidders, bidders have the incentive to reduce demand. Direct evidence of demand reduction was seen in the nationwide narrowband auction. The largest bidder, PageNet, reduced its demand from three of the large licenses to two, at a point when prices were still well below its marginal valuation for the third unit (Cramton 1995). PageNet felt that, if it continued to demand a third license, it would drive up the prices on all the others to disadvantageously high levels.

An examination of the bidding in the AB auction is suggestive that the largest bidders did drop out of certain markets at prices well below plausible values, as a result of either demand reduction or tacit collusion.

Further evidence of demand reduction comes from the C auction. One large bidder defaulted on the down payment, so the FCC reauctioned the licenses. Interestingly, the licenses sold for 3 percent more than in the original auction. Consistent with demand reduction, NextWave, the largest winner in the C auction, bought 60 percent of the reauctioned spectrum. This occurred despite the fact that NextWave was not the second-highest bidder on any of these licenses in the original auction. NextWave was able to bid aggressively in the reauction, knowing that its bidding would have no affect on prices in the original auction.

Engelbrecht-Wiggans and Kahn (1999) and Brusco and Lopomo (1999) show that for an auction format like the FCC's, where the bidding occurs in rounds and bidding can be done on distinct units, that there exist equilibria where bidders coordinate a division of the available units at low prices relative to own values. Bidders achieve these low-revenue equilibria by threatening to punish those bidders who deviate from the cooperative division of the units. The idea in these papers is that bidders have the incentives to split up the available units ending the auction at low prices. With heterogeneous goods and asymmetric bidders in terms of budgets, capacities, and current holdings of complementary goods, it is unlikely that bidders would be aware of a simple equilibrium strategy that indicates which licenses to bid on and which to avoid. However, bidders in the FCC auctions, especially the DEF auction, took advantage of signaling opportunities to coordinate how to assign the licenses. With signaling, bidders could indicate which licenses they most wanted and which licenses they would be willing to forgo. Often this communication took the form of punishments.

Cramton and Schwartz (1999) examine collusive bidding strategies in the DEF auction. During the DEF auction the FCC and the Department of Justice observed that some bidders used bid signaling to coordinate the assignment of licenses. Specifically, some bidders engaged in *code bidding*. A code bid uses the trailing digits of the bid to tell other bidders on which licenses to bid or not bid. Since bids were often in millions of dollars, yet were specified in dollars, bidders at negligible cost could use the last three digits—the trailing digits—to specify a market number. Often, a bidder (the sender) would use these code bids as retaliation against another bidder (the receiver) who was bidding on a license desired by the sender. The sender would raise the price on some market the receiver wanted, and use the trailing digits to tell the receiver on which license to cease bidding. Although the trailing digits are useful in making clear which market the receiver is to avoid, *retaliating bids* without the trailing digits can also send a clear message. The concern of the FCC is that this type of coordination may be collusive and may dampen revenues or efficiency.

The DEF auction was especially vulnerable to collusive bidding, it featured both small markets and light competition. Small markets enhanced the scope for splitting up the licenses. Light competition increased the possibility that collusive bidding strategies would be successful. Indeed, prices in the DEF auction were much lower than prices in the two earlier broadband PCS auctions.

From a strategic viewpoint, the simultaneous ascending auction can be thought of as a negotiation among the bidders. The bidders are negotiating how to split up the licenses among themselves, but only can use their bids for communication. The auction ends when the bidders agree on the division of the licenses. Retaliating bids and code bids are strategies to coordinate on a split of the licenses at low prices. In addition, bidders with a reputation for retaliation may scare off potential competitors. Cramton and Schwartz (CS) hypothesize that bidders who commonly use these strategies pay less for the spectrum they ultimately win.

CS find that six of the 153 bidders in the DEF auction regularly signaled using code bids or retaliating bids. These bidders won 476 of the 1,479 licenses for sale in the auction, or about 40% of the available spectrum in terms of population covered. Controlling for market characteristics, these signaling bidders paid significantly less for their licenses.

Further evidence that retaliation was effective in reducing prices is seen by the absence of arbitrage between the D and E blocks in each market. In particular, CS find that there was a tendency for bidders to avoid AT&T, a large bidder with a reputation for retaliation. If bidders did not care about the identity of the high bidder, they would arbitrage the prices of the D and E blocks, and bid against AT&T if the other block was more expensive. This did not happen. Even when the price of the other block was 50% higher, bidders bid on the higher priced block 27% of the time, rather than bid against AT&T.

Following the experience in the DEF auction, the FCC restricted bids to a whole number of bid increments (typically between 1 and 9) above the standing high bid. This eliminates code bidding, but it does nothing to prevent retaliating bids. Retaliating bids may be just as effective as code bids in signaling a split of the licenses, when competition is weak.

The auctioneer has many instruments to reduce the effectiveness of bid signaling. These include:

- Concealing bidder identities. This prevents the use of targeted punishments against rivals. Unless there are strong efficiency reasons for revealing identities, anonymous auctions may be preferable.

- Setting high reserve prices. High reserve prices reduce the incentive for demand reduction in a multiple-item auction, since as the reserve price increases the benefit from reducing demands falls. Moreover, higher reserve prices reduce the number of rounds that the bidders have to coordinate a split of the licenses and still face low prices.

- Offering preferences for small businesses and non-incumbents. Competition is encouraged by favoring bidders that may otherwise be disadvantaged ex ante. In the DEF auction, competition for the D and E license could have been increased by extending small business preferences to the D and E blocks, rather than restricting the preferences to the F block.

- Offering larger licenses. Many small licenses are more easily split up. At the other extreme a single nationwide license is impossible to split up. In the absence of synergies, such extreme bundling may have negative efficiency consequences, but improve revenues.

In auctions for identical items, the inefficiencies of demand reduction can be eliminated with a Vickrey (1961) auction. Alternatively, one can use Ausubel's (1997) ascending implementation of the static Vickrey auction, which has the additional advantages of an ascending-bid design. However, most spectrum auctions are not for identical items, so Vickrey-type mechanisms often are not practical.

## 6 Lessons learned and auction enhancements

The FCC auction rules have evolved in response to the experience of more than two dozen auctions. An examination of this evolution is instructive. Despite many enhancements, the FCC spectrum auctions have retained the same basic structure, a strong indication of an excellent initial design. The intent of the changes were to reduce speculative bidding, to avoid collusion, and to speed the auction along.

*Elimination of installment payments*. A potentially serious inefficiency in the C auction was speculative bidding caused by overly attractive installment payment terms. Bidders only had to put down 5 percent of their bids at the end of the auction, a second 5 percent at the time of license award, and then quarterly installment payments at the 10-year Treasury rate with interest-only payments for the first 6 years. These attractive terms favor bidders that are speculating in spectrum. If prices go up, the speculators do well; if prices fall, the speculators can walk away from their down payments. Indeed, spectrum prices did fall after the C auction, and most of the large bidders in the C auction defaulted on the payments. As a result of this experience, the FCC no longer offers installment payments. Bids must be paid in full when the licenses are awarded.

*Click-box bidding*. Bidders in FCC auctions no longer enter bids in dollars. Rather, the bidder indicates in a click-box the number of bid increments from 1-9 that it wishes to bid above the standing high bid. If the standing high bid is 100 and the minimum bid increment is 10%, then the allowable bids would be 110, 120, …, 190, corresponding to the allowable increment bids of 1, 2, …, 9. This approach solves two problems. First, it eliminates code bidding. Bidders can no longer use the trailing digits of bids to signal to other bidders who should win what. Second, it reduces the possibility of mistaken bids. There were several instances of bidders adding too many zeros to the end of their dollar bids. With click-box bidding, substantial jump bids are permitted but not gross mistakes.

The downside of click-box bidding is the greater possibility of tie bids. This turns out not to be a serious problem. Although ties do occur early in the auction, it is unlikely that the final bid on a license involves a tie. Still ties do occur, and so the FCC tie-breaking rule takes on greater importance. The FCC breaks ties with the time stamp. Bids entered earlier have preference. Since bidders often have a mild preference for being the standing high bidder, it is common for bidders to race to enter their bids early in the round to win ties. Such behavior is undesirable, and so the FCC is now considering a random tie-breaking rule in future auctions.

*License-specific bid increments*. In early auctions, the FCC used the same percentage increment for all licenses. This was fine for auctioning a handful of similar licenses. However, when auctioning hundreds of heterogeneous licenses, it was found that some licenses would have a lot of bidding activity and others would have little activity. To speed the auction along, it makes sense to use larger bid increments for more active licenses. In recent auctions, the FCC adjusts the bid increments for each license based on the license’s history of bid activity, using an exponential smoothing formula. Percentage increments tend to range between 5 and 20 percent, depending on prior activity. More active licenses have a larger increment.

*Limit the use of withdrawals*. Bid withdrawals were introduced to permit bidders to back out of a failed aggregation. The DEF auction had 789 withdrawals. Few if any of these withdrawals were related to failed aggregations. Rather, most of the withdrawals appear to have been used as a strategic device, in one of two ways: (1) as a signal of the bidder’s willingness to give up one license in exchange for another or (2) as part of a parking strategy to maintain eligibility without bidding seriously. This undesirable use of withdrawals was also observed in other auctions. As a result, the FCC now only allows withdrawals in at most two rounds of the auction for any bidder. This enables the bidder to back out of up to two failed aggregations, and yet prevents the frequent strategic use of withdrawals.

*Combine bid submission and withdrawal phases*. The FCC originally divided a round of bidding into two phases, a bidding phase followed by a withdrawal phase. The separation of these phases was largely a historical artifact and provides little benefit. Its main effect was to impede the pace of the auction.

The FCC has since combined the two phases into one. With the combined procedure, bid submission consists of two steps: withdrawal followed by submission. In the withdrawal step, the bidder may withdraw on any or all licenses on which it is the high bidder. Then, in the bid submission step, the bidder places any desired new bids, with available eligibility increased to reflect the withdrawals. Hence, a bidder withdrawing in New York can then place a bid (in the same round) on Los Angeles, because of the eligibility freed by the New York withdrawal.

*Faster rounds*. The FCC's auction system now permits much faster rounds than the initial implementation. In many auctions, bidding activity is slow in the later part of the auction. Hence, being able to conduct 20 or more rounds per day is important in speeding the auction along.

*Minimum opening bids*. Early FCC auctions did not use minimum opening bids; any opening bid greater than zero was acceptable. The FCC now sets substantial minimum opening bids. These bid limits both increase the pace and reduce the potential for collusion. By starting at a reasonably high level, the bidders have fewer rounds to resolve their conflicts at low prices. The benefit of collusive strategies is reduced.

## 7 Package bidding

One auction enhancement that has received considerable attention is package bidding. A key simplification of the FCC auctions is only allowing bids on individual licenses. This works well in settings where there are not large complementarities across licenses, or if there are large complementarities, then where the complementarities are similar among the bidders. In such a setting, the exposure problem is slight. There is little likelihood that a sincere bidder will get stuck with licenses it does not want. However, in auctions where license complementarities are large and differ among bidders, then the exposure problem may be substantial. In this latter case, allowing package bids—all-or-nothing bids on collections of complementary licenses—can reduce the exposure problem and improve efficiency. Efficiency can also be improved by reducing the incentives for demand reduction by large bidders.

Auctions with package bidding, often referred to as combinatorial auctions or package auctions, are actively being researched. In May 2000, the FCC sponsored a conference on the topic.[2] A goal of the conference was to determine the best way to introduce package bidding in the 700 MHz auction to take place in Fall 2000. The 700 MHz auction represented a good test-case for package bidding for two reasons. First, it is a relatively simple case, since it involves only 12 licenses: 2 bands (one 10 MHz and

---

[2] The conference materials are available at http://wireless.fcc.gov/auctions/31/. This site also includes the comments, reply comments, and FCC documents on package bidding.

one 20 MHz) in each of 6 regions. Second, perspective bidders had expressed interest in alternative packaging. Those bidders intending to provide a fixed high-speed data service desired the full 30 MHz in a particular region. Some mobile wireless providers desired individual licenses to add capacity in congested regions or to fill out their footprint. Still others desired nationwide packages to offer a nationwide mobile service.

The conference resulted in FCC Public Notice DA00-1075 seeking comment on modifying the simultaneous ascending auction to allow package bidding in the 700 MHz auction. After comments and reply comments were received, the FCC issued Public Notice DA00-1486 adopting and describing the package bidding rules for the 700 MHz auction. I briefly describe the approach taken by the FCC in this auction. The rules are intended to improve the efficiency of the auction by avoiding the exposure problem, while limiting the threshold problem.

A bidder can bid on the individual licenses as in the standard simultaneous ascending auction. In addition, a bidder can place all-or-nothing bids on up to twelve packages, which the bidder determines at any point in the auction. In this way the bidder can avoid the exposure problem when licenses are complements. The provisional winning bids are the set of consistent bids that maximize total revenues. Consistent bids are bids that (1) do not overlap, and (2) are made or renewed in the same round. Bids made by a bidder in different rounds are treated as mutually exclusive.[3]

Limiting each bidder to twelve bidder-specific packages simplifies the auction, and still gives the bidders great flexibility in expressing synergies for various license combinations. The FCC's original proposal allowed only nine package bids: the six 30 MHz regional bids, and three nationwide bids (10, 20, or 30 MHz). Although these nine packages were consistent with the expressed desires of many perspective bidders, others felt that the nine packages were too restrictive.

The activity rule is unchanged, aside from a new definition of activity and a lower activity requirement of 50%, giving the bidders greater flexibility in shifting among packages. A bidder must be active on 50% of its current eligibility or its eligibility in the next round will be reduced to two times its activity. A bid counts as activity if (1) it is part of a provisionally winning set in the prior round, or (2) it is a new bid or a renewal of a provisionally winning bid in the prior round. A bidder's activity level is the maximum number of bidding units a bidder can win considering only those licenses and packages on which the bidder is active. Bids made in different rounds are treated as mutually exclusive; hence, a

---

[3] This and several other features of the design were recommended by Paul Milgrom. See http://wireless.fcc.gov/auctions/31/.

bidder wishing to add a license or package to its provisional winnings must renew the provisional winning bids in the current round.

The FCC adopted a two-round simultaneous stopping rule. The auction ends after two consecutive rounds of no new bids on any licenses or packages. Renewed bids do not count as new bids. The two-round approach gives bidders fair warning that the auction may end if they do not place a new bid.

The determination of minimum bids is an important change in the rules, since it impacts the extent of the threshold problem faced by those bidding on individual licenses or small packages. The minimum bid on a license or package is the greater of: (1) the minimum opening bid, (2) the bidder's own previous high bid on that package plus x%, and (3) the number of bidding units of the package times the lowest $/bidding unit on any package in the last five rounds. The FCC specifies x, and retains discretion to adjust minimum bids on a license-by-license or package-by-package basis.

The key feature of this minimum bid rule is point (2), which makes the minimum bid depend on the bidder's prior high bid for the package. This recognizes that since a bidder's bids in different rounds are mutually exclusive, another bidder's bid on a package can be a provisionally winning bid even if it is less than the high bid of the prior round. Hence, the rules allow bids that are below another's prior high bid. Points (1) and (3) limit how low a bidder can bid when it starts out bidding on a new package. The bid must be at least as great as the minimum opening bid and the least expensive package on a per unit basis.

The FCC will continue to use "click box" bidding, in which the bidder specifies either the minimum bids or an integer between 1 and 9. A bid of 1 is the minimum bid plus x% of the minimum bid; a bid of 2 is the minimum bid plus 2x% of the minimum bid; and so on. The FCC considered limiting bids on packages to the minimum bid to reduce the threshold problem; however, it was felt that the revised minimum bid rule adequately addressed the threshold problem.

Another change is allowing bidders to submit "last and best" bids. Last and best bids can be for any amount between the bidder's prior high bid and the minimum bid. A bidder cannot bid again after placing one or more last and best bids.

A bidder can renew the highest bid it made on any license or package. Renewing a bid does not increase the bid amount. Renewed bids are needed, since bids in different rounds are treated as mutually exclusive. Thus, if a bidder wishes to win both its provisional winners from the prior round plus a new license, it must bid on the new license and renew the provisional winners. Activity credit is not given for renewing a bid that is not a provisional winner.

Provisional winning bids are the set of "consistent" bids (bids that do not overlap and are made or renewed by a bidder in the same round) that maximize revenues as of the current round. Winning bids are the provisional winning bids at the end of the auction. Ties are broken randomly. Licenses on which no bids have been submitted are treated as if the minimum opening bid was placed. This is consistent with the minimum opening bids reflecting the FCC's opportunity cost of selling the licenses.

Treating a bidder's bids in different rounds as mutually exclusive is an important feature. First, it gives bidders a vehicle for submitting contingent "or" bids. If the bidder desires one package or the other, but not both, the bidder simply bids for the two packages in separate rounds. Bidders can shift to backup strategies without fear that they will win a collection of licenses they do not desire. Second, it encourages sincere bidding early in the auction, since bids placed early in the auction may emerge as winning bids. When submitting its bids in a round, the bidder is saying that it is happy to win any of the submitted bids, including renewed bids, at the prices bid.

Bid withdrawals are not permitted. In an auction without package bidding, withdrawals were needed as a device for backing out of a failed aggregation. With package bidding, withdrawals are not needed. There is no exposure problem, since the bidder can bid all-or-nothing on a package of complementary licenses.

Allowing package bids is a major change from the original FCC design. Bidder incentives are fundamentally altered. Large bidders, in addition to not facing an exposure problem, have less of an incentive for demand reduction. Small bidders now face a negotiation with each other on how to top large package bids. All bidders will need to rethink their strategies. Relative to the standard auction, which favored small bidders, the package auction favors large bidders.

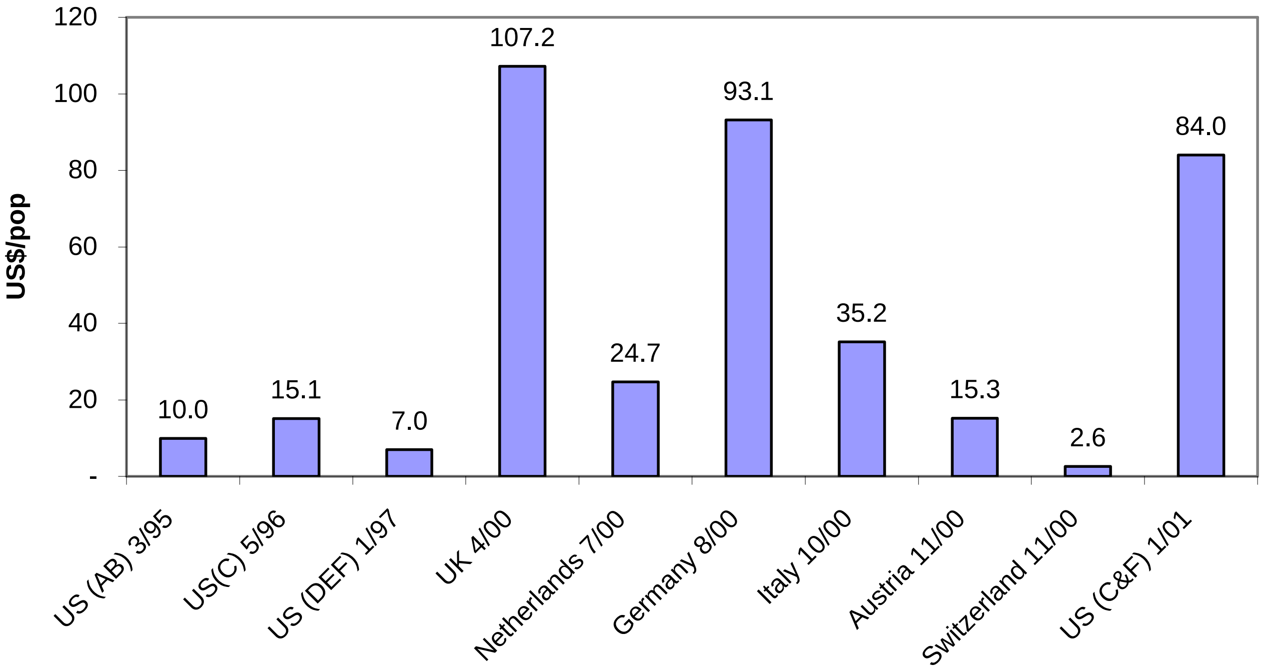
The FCC's package auction is an important innovation. Implementing such an auction poses many challenges for the FCC. It is not surprising that it took several years to introduce package bidding. Even now it is uncertain how well this design will perform in practice compared with the standard auction without package bidding. Whether the package auction is an improvement surely depends on the setting.

# 8 UMTS auctions in Europe and Asia

European and Asian countries currently are in the process of assigning Universal Mobile Telecommunications System (UMTS) licenses, which will be used for third-generation mobile wireless services. Many countries decided to use an auction to assign the licenses (e.g., UK, Netherlands, Germany, and Switzerland); other countries (e.g., France, Spain, and Sweden) decided on a beauty contest; and still others (e.g., Italy) decided on a hybrid beauty contest/auction. The allocation of UMTS spectrum is European-wide, although individual countries can determine there own band plans. Nearly all countries are assigning between four and six national licenses.

The early European auctions conducted in 2000 raised nearly $100 billion. An additional expense of at least $100 billion will be required to build the infrastructure necessary to provide service. In countries like the UK and Germany, which fetched the highest prices the license cost per person amounts to about $100 per person. These staggering sums have led many to question the desirability of auctions for assigning spectrum licenses.

Figure 1. Mobile Wireless Price Comparison (2x10 MHz + 5 MHz)



In fact, auction prices have varied considerably over time and over markets. This is seen in Figure 1, which presents the per person price of a 20 MHz license (2×10 MHz paired) in several major spectrum auctions.[4] For comparison purposes, Figure 1 also shows past and current US auctions of 2G spectrum. The first three US auctions occurred over three years before the 3G auctions in Europe. The fourth US auction concluded in January 2001 with a price comparable to the highest 3G prices. Part of price

---

[4] Most of the European licenses also included 5 MHz unpaired spectrum. However, these auctions have shown that the bidders place little value on this unpaired spectrum, so I ignore the unpaired spectrum in the price comparison. In the US C-block auction, bidders received attractive installment payment plans. I discount these prices by 40% to reflect the value of the installment payments.

variation is explained by the different times at which the auctions occurred. Part of the difference in the European prices is explained by the size of the various countries. Markets like the UK and Germany are thought to have more value, even on a per person basis, than the Netherlands and Switzerland. Still there is much variation to explain. The primary determinant of prices appears to be the level of competition going into the auction, rather than the subtle differences in auction design across the various countries. Competition in the auction is largely endogenous, since it is the result of partnership negotiations among potential bidders.

The first countries to auction (UK, Netherlands, and Germany) used a simultaneous ascending auction. In the UK and the Netherlands, the auction design is especially simple, since a bidder can win at most a single license. Hence, there is no incentive for demand reduction.

An incumbent provider of first- and second-generation mobile services in a market tends to have a much higher value for a license than a new entrant. The incumbent’s existing infrastructure and customer base yields cost savings in building out a service and attracting customers. Also, an incumbent’s failure to win a license would adversely impact its existing business. Hence, it is likely that incumbents will win licenses. As a result, the outcome of the auction depends greatly on the number of licenses that are auctioned relative to the number of incumbents. The UK government initially intended to auction four licenses, but there was a concern that this would damage auction revenues, since potential new entrants might fear that it is pointless to compete against the four strong incumbents. The final design involved the auction of five licenses, which guaranteed that a new entrant would win a license. In contrast, in the Netherlands, there are five incumbents and five UMTS licenses.

The UK UMTS auction was the largest auction in history, generating $35 billion in revenues. Four incumbents and nine potential entrants competed in the auction, which lasted 150 rounds. The four incumbents, British Telecom, Vodafone, Orange, and One 2 One, each won a license, as did the new entrant TIW. Vodafone’s 2×15 MHz license sold for $9.5 billion, or $160 per person; the other incumbent licenses sold for similar prices on a per MHz basis. This amount far exceeded industry expectations before the auction. In contrast, the average price paid in 1995 in the FCC’s AB auction for a 2×15 MHz license was $15.5 per person, less than one-tenth of the UK price.

Why were the UK prices so high? There are several factors. First, the 1995 price of $15.5 per person in the US is out of date. US prices now are much higher. For example, early in 2000, Nextel offered to buy Nextwave’s spectrum for $8.3 billion, a price of about $80 per person. Second, unlike in the US auction, there was no possibility for demand reduction. Bidders had every incentive to bid up to their values. Third and likely most important, the bidding was especially competitive, since this was the first in a sequence of UMTS auctions throughout Europe. A winner in the UK auction is well positioned for subsequent UMTS auctions. Hence, a bidder can view the UK auction as a foot-in-the-door to Europe. To the extent that a UK license is complementary with UMTS licenses in other countries, then we should expect the UK licenses to sell for a premium, recognizing this complementary value.

In the German auction, each bidder bid for either two or three of the twelve available 2×5 MHz blocks; hence, there will be between four and six winners. The German auction had the apparent advantage that it lets the bidding determine how many UMTS competitors there will be. If competition among new entrants is intense, there can be six winners, presumably the four incumbents plus two new entrants. Jehiel and Moldovanu (2000) argue that the design is biased against new entry, since the incumbents have substantially higher values because of their incumbent position and benefit from excluding new entrants. However, it is possible that the two weakest incumbents may be willing to bid for just two blocks, making room for a new entrant. The question is whether the benefit from demand reduction more than compensates for the reduced profits in a five-player vs. a four-player market. Probably a better design would set-aside two blocks for a new entrant and then let the bidding determine whether there would be four or five winners for the remaining ten blocks.

Following the $35 billion UMTS auction in the UK, the Dutch government expected to raise $8.7 billion in its auction. The Dutch government arrived at this figure by simply scaling down the UK amount for the smaller population in the Netherlands (15 vs. 59 million people). Confident of a huge windfall, the government cancelled its July bond issue. Their confidence may be a mistake. The reality is that the UK and Dutch auctions are quite different despite the fact that both use the simultaneous ascending auction to auction off five third-generation mobile licenses.

In the UK, the guaranteed success of at least one new entrant encouraged participation in the auction. In the Netherlands, with five incumbents bidding for five licenses, the logical outcome is for the five incumbents to win licenses. Recognizing the difficulty of winning a license, potential entrants have strong incentives to partner with the incumbent bidders. This is exactly what happened. Although initially there were several strong potential entrants, all partnered with one of the incumbents before the auction began. The strongest entrant, Deutsche Telecom, partnered with the weakest incumbent, Ben; DoCoMo and Hutchinson partnered with KPN; and NTL was already effectively partnered with Dutchtone (France Telecom has a large interest in both). This left one weak entrant in the bidding. At the beginning of the auction, just six bidders were competing for five licenses: five strong incumbents and one weak potential entrant (Versatel).

To make matters worse, the government specified minimum opening bids that decline in the first three rounds if a license does not receive a bid. The two large licenses (15 MHz-paired) start at 100 million guilders, but fall to 75 after one round of inactivity, 35 after two rounds, and 0 after three rounds; similarly, the three 10 MHz-paired licenses start at 90, but drop to 60, 30, and then 0, with each round of inactivity. Bidders were given three waivers of the activity rule that otherwise would require them to be active in each round.

The strategic use of waivers in this environment should be obvious. Even if the other five bidders bid in the first round, it is extremely unlikely that each of the five licenses would receive a bid. Hence, by using a waiver in the first round, a bidder can get the minimum opening bid to drop substantially. In fact, five of the six bidders saw this strategy. Only Libertel bid in the opening round, placing a 100 million guilder bid on B. (Libertel is 70% owned by Vodafone, the company that won the B license in the UK auction.) In the second and third rounds, the five bidders that needed to bid again used waivers. So going into the fourth round, the minimum bids were 0 on all licenses, but the B license, which stood at 110 million guilders. After 175 rounds of bidding, the three 10 MHz licenses were priced at 1/8th of the minimum opening bid (11 million guilder).

The Dutch auction rules also did not include the customary language that the auctioneer has the right to cancel the auction at any time. If Versatel decides to drop out at low prices the auction will end at only a tiny fraction of the $8.7 billion figure the government is hoping for.

The 3G auctions provide an excellent test of auction theory with multiple items. These auctions have been strategically simple and are extremely high stake. For example, the German and Austrian 3G auctions—as well as an earlier 2G German auction—provided relatively clean tests of demand reduction. The theoretical predictions on demand reduction were borne out empirically in the final outcomes of these auctions. At the same time, one would have imagined that all of the bidding behavior, at least by the eventual winners, could be easily understood as equilibrium behavior in a profit-maximizing model. However, this does not always appear to be the case.

One explanation for non-profit maximizing bidding is the principal-agent problem between the shareholders and the CEO making the bidding decisions (Ausubel and Cramton 2001). At times the CEO may not fully represent shareholder interests. For example, CEO’s may sometimes fail to fully appreciate the economics of demand reduction, and fail to reduce demand as early as they should. In particular, in the German auction, Deutsche Telekom (DT) was in a position to likely end the German auction by dropping from demanding three blocks to demanding two blocks, at well before the final prices. Instead, DT continued bidding for three blocks for a time, ultimately buying the two blocks that it could have bought earlier, but paying about $2 billion more. This bidding behavior may have more to do with the preferences (and fears) of the CEO, rather than the interests of the shareholder.

A second source of distortion is that the CEO simply acts as humans do in auctions, making some of the same mistakes that are frequently observed in the laboratory (Kagel and Roth 1995). An example similar to the DT example, but with a different outcome occurred in the US C&F auction. In New York, three licenses were up for bid. After round 14, only the three largest bidders (Verizon, Cingular, and AT&T) were competing for the three licenses. At this point prices were at $782 million. Verizon, however, continued to bid for two licenses throughout the auction, creating excess demand until Cingular finally dropped out when Verizon's price exceeded $2 billion per license. Why did Verizon continue to push the price up on both of its licenses rather than ending the bidding at a fraction of the eventual price? One explanation is that the Verizon CEO felt that he would look bad, pushing the prices up and then eventually settling for one license. This gives the CEO an incentive to "throw good money after bad," a phenomenon for which there is ample experimental support.

## 9 Advice to governments

Important lessons about spectrum auction design can be gleaned from recent experience.

### *9.1 Allocating the spectrum is just as important as its assignment*

There are two steps in making spectrum available to companies. The first step is the allocation of the spectrum for licensing. The allocation defines the license (the frequency band, the geographic area, the time period, and the restrictions on use). The second step is assigning the licenses to particular companies. Although my focus has been on assigning the licenses, since that is what the spectrum auctions are asked to do, the allocation step often is more important. Arguably the greatest economic gains will come from better allocation of spectrum, rather than from improved methods of assigning the spectrum. This is because current spectrum auctions already are highly efficient. In contrast spectrum allocations often are far from efficient.

Determining spectrum allocations involves complex political, engineering, and economic factors. Finding suitable spectrum for new uses is difficult. Often there are incumbent spectrum users. Ideally, one would want market-based tests to determine what spectrum should be auctioned and how it should be structured, but such tests are hard to construct. Political compromises frequently trump good economics. This is especially the case when the competing uses include several constituencies, such as broadcasting, commercial, public safety, and military use.

Finally, the allocation can have a pronounced effect on the success of a particular auction design. For example, having five licenses in the UK UMTS auction, rather than four, was critical in stimulating competition (Klemperer 1998).

### 9.2 Use care when modifying successful rules

Simultaneous ascending auctions overall have been highly successful in the US and many other countries. Recent FCC auction rules should be a starting point for any government considering spectrum auctions. Modifications to the rules should be considered carefully. The various rules interact in often subtle ways. An apparently innocent change can have disastrous consequences. The interaction between waivers and the declining schedule of minimum opening bids in the Dutch UMTS auction is an example.

Still it is important to recognize that different settings often require a different auction design, as is emphasized in Klemperer (2000). For example, an ascending auction may be inappropriate in situations where competition is weak (Cramton 1998).

### 9.3 Allow discretion in setting auction parameters

The simultaneous ascending auction has a number of parameters (minimum opening bids, minimum bid increments, activity requirements, and rounds per day) that let the government control the pace of the auction. It is fine for the government to specify guidelines on how it is likely to set parameters, but eliminating all discretion is a bad idea. There are simply too many unknowns going into the auction for the government to specify all parameters in advance. The parameters should be adjusted during the auction to balance the goals of a timely assignment and an efficient assignment. The bidders need time to adjust strategies in light of information revealed in the bidding. Too much haste may lead to bidder error and inefficient assignments. Time also may be needed for bidders to secure additional capital if prices are higher than expected. On the other hand, setting the bid increment too low (e.g., 1%) near the end of the auction can result in days of bidding without much progress.

### 9.4 Reduce the effectiveness of bidders' revenue-reducing strategies

The information and flexibility available to the bidders in a simultaneous ascending auction is a two-edged sword. Although desirable in reducing bidder uncertainty and promoting efficient license aggregations, the information and flexibility—in certain circumstances—can be used to reduce auction prices. In particular, revenue-reducing strategies may be effective when bidder competition is weak and when bidders already have a sense of who should win what. In this case, the auction is best thought of as a negotiation among the bidders, in which bidders are only able to communicate through their bids. The auction ends when there are no disagreements about who should win what.

As discussed earlier, one common revenue-reducing strategy is demand reduction: the tendency for a bidder to reduce its spectrum demands, knowing that demanding less will tend to reduce spectrum prices. This is a unilateral strategy that is best addressed in the choice of the band plan and geographic scope of the licenses. License structures that make it more difficult for the bidders to split up the spectrum are less vulnerable to demand reduction. For example, offering large nationwide licenses, in which no bidder can win more than one, prevents the bidders from splitting up the spectrum at auction.

The second revenue-reducing strategy is retaliation. This can be thought of as coordinated demand reduction. It is sending another bidder the message that they should stay off your licenses, if they want you to stay off their licenses. Retaliation is especially clear in early auctions where it is possible to use the trailing digits of bids to identify relevant markets. The bidders are effectively able to say things like, “I’ll stay out of New York, if you stay out of Los Angeles.” This tactic is eliminated by truncating bids to three significant digits, or only allowing bids in integer multiples of the bid increment. However, it is still possible for bidders in certain circumstances to use retaliation to keep prices low. Retaliation is best minimized through careful choice of activity rules, minimum opening bids, and bid increments. An anonymous auction can be used in settings where collusion is likely.

## *9.5 Use spectrum caps to limit anticompetitive concentration*

A spectrum cap is a direct method of limiting the concentration of spectrum for a particular type of service in a particular area. Its advantage is that it is a bright-line test that is easy to enforce, both before and after the auction. In the US, it has played a critical role in ensuring that there are many competitors for mobile wireless services in each market. This competition has led to clear gains for consumers. Its disadvantage is that it is overly simplistic. Spectrum caps cannot take into account the specifics of each situation, and determine whether consumers would be made better or worse off with greater concentration of ownership.

The best policy on spectrum caps is a middle ground, where binding caps are imposed in initial auctions, but then these caps give way once it is believed that vigorous competition has been established. Then individual mergers can be reviewed on a case-by-case basis.

In setting and revising spectrum caps, governments should err on the side of too stringent a cap, since it is much harder to break up a firm than to allow a merger. If concentration is viewed as a potential problem going into an auction, then spectrum caps, rather than case-by-case review, must be used, since only caps can provide an instantaneous determination of what is allowed and what is not. Such a rapid response is essential in a simultaneous ascending auction. Bids must be binding commitments until they are topped. Hence, at every point in the auction, the bidders must know what is allowed and what is not.

Typically, spectrum caps lower auction revenues, but there is one important exception. In situations where incumbent bidders have an advantage, a spectrum cap may actually increase revenues and promote efficiency. In such a situation without a spectrum cap, non-incumbents may be unwilling to participate in the auction, knowing that the incumbents will ultimately win. As a result, in the auction without the cap only the incumbents show up, there is a lack of competition, and the incumbents split the licenses up among themselves at low prices. With the cap, the non-incumbents know that non-incumbents will win licenses, giving them the incentive and ability to secure the needed financing from capital markets. A competitive auction with market prices results. This phenomenon of incumbent bidders getting good deals, because of a lack of non-incumbent competition has been seen in some US auctions, but is most vivid in the Dutch UMTS auction.

### *9.6 Implement special treatment for designated entities with care*

One of the auction objectives that the US Congress gave the FCC is to have a diversity of auction winners. The FCC was instructed to encourage participation by small businesses and women- or minority-owned firms, so called “designated entities.”

While small and diverse owners may well be a desirable goal for broadcast media with editorial content, the same arguments likely do not apply to mobile wireless communications. Special treatment to designated entities is to some extent premised on the idea that small is beautiful. But what we have learned in the last several years is that there are significant scale economies in wireless communications. Part of the scale economy is the bargaining advantage it creates with equipment suppliers. Another part is scale economies in marketing. But perhaps the largest is the value that consumers place on seamless roaming. As a result, the marketplace has shifted toward nationwide services in most wireless categories. These nationwide services are necessarily billion dollar deals, or tens-of-billions in the case of broadband mobile services. What consumers need is a variety of strong national competitors. In many cases, the small regional players cannot compete. The designated entity rules may simply be setting up the small businesses for failure. This is not desirable, especially given that the FCC’s unjust enrichment rules, discussed below, effectively prevent resale to the higher-valued use should failure occur.

On balance, the best policy may be to abandon favors to designated entities, and to use spectrum caps to guarantee new entry where desirable and to prevent over-consolidation of spectrum. An alternative is to offer non-incumbents bidding credits to encourage new entry. My reason for this conclusion has to do with the practical difficulties of effectively implementing favors for designated entities, which I discuss below.

The FCC has used bidding credits, set-asides, and installment payments to encourage the participation and success of designated entities. The idea is that without special treatment, these small businesses would find it difficult to compete with the large incumbents. The favored treatment can serve to “level the playing field,” and thereby foster innovation and intensify competition.

Although this is a valid point in theory, and even has some empirical support (Ayres and Cramton 1996), governments must be cautious when using favors for designated entities. A vivid example is the FCC’s only major setback, the C-block broadband PCS auction. (Other disappointing auctions were IVDS and WCS, but none have involved the economic loss seen in the C-block.) The auction failed largely because of overly attractive installment payments (10% down and 6-year interest-only at the risk-free 10-year Treasury rate). This encouraged speculative bidding, which led to all the major bidders defaulting and declaring bankruptcy. Even now, years after the auction, much of this C-block spectrum lies unused, tied up in bankruptcy litigation. Installment payments were a bad idea, because they advantaged the bidders with the most speculative business plans. In addition, installment payments put the FCC in the role of banker, an activity for which the FCC has no advantage. Since the C-block experience, the FCC no longer offers installment payments.

The two other instruments to favor designated entities—set-asides and bidding credits—may be desirable in special situations. The typical situation is one where the government is attempting to encourage competition in the auction and the post-auction market for wireless services. By leveling the playing field between incumbents and new entrants, competition may be enhanced.

Still, set-asides and bidding credits have serious potential problems. Gauging the right level of set-asides or bidding credits is extremely difficult. Also, it is nearly impossible to target the favor to the desired group. The creation of fronts, carefully constructed to satisfy the rules but circumvent their intent, has been a constant problem in the FCC auctions.

One general rule, whether using set-asides or bidding credits, is that it is best for incumbents and non-incumbents to compete in the same auction. Then if competition among non-incumbents is sufficiently robust, the non-incumbents will be able to spill over to the licenses that incumbent bidders can bid on. This spillover increases competition, and hence revenues in the auction.

Another problem with favors for designated entities is their impact on the resale of spectrum. The FCC auction rules prohibit resale to a non-designated entity for a period of time, and include an “unjust enrichment” provision that requires that the FCC be paid back the bidding credit plus interest. The reality has been that the bidding credits are often bid away by competition among designated entities. Indeed, even after accounting for the value of the installment payments and the bidding credits, the C auction resulted in prices that were well above what the large firms paid in the AB auction. Given these facts, it is difficult to understand why the small firms are required to pay a huge “unjust enrichment” penalty, when there is no unjust enrichment. As it stands, the penalty is so large that it is often an insurmountable barrier to trade.

Perhaps the most serious problem with favors to designated entities is that they greatly complicate the auction process. Too often the rules for designated entities become a central issue in establishing the auction procedures. These rules are complex. They are difficult to write, difficult to enforce, and difficult to defend. The absolute worst outcome in a spectrum auction is having the licenses tied up in litigation. Until the litigation is resolved the building of communication services cannot begin. Even the risk of litigation can have a disastrous effect on auction participation, and hence revenues.

### 9.7 Implementing an effective auction takes time and involves difficult tradeoffs

A second FCC auction disappointment was the Wireless Communication Services (WCS) auction, held in April 1997. Revenues in this auction were a tiny fraction of what they might have been. The main problem was the stringent out-of-band emission limit. Equipment manufacturers warned that this would threaten the commercial viability of this spectrum. The low prices at auction and the absence today of activity in this band appears to confirm that the equipment manufacturers were right. At the time of the decision, the FCC was facing a difficult tradeoff between the rights of prior winners of neighboring licenses and the WCS use. Such decisions are always difficult, but the FCC was under intense time pressure to meet the timetable that Congress set for the auction. This aggressive timetable may well have led the FCC to make a too-hasty decision on interference rules, which damaged the value of this spectrum. Congress’s desire for receiving revenues according to its fiscal calendar may have resulted in substantially reduced auction revenues.

### 9.8 Facilitate efficient clearing when auctioning encumbered spectrum

An issue of increasing importance is the auctioning of encumbered spectrum. Many of the FCC auctions are for overlay licenses (the PCS and 700 MHz auctions are examples). An overlay license is for the portions of the band that are not occupied by incumbent licensees. Effectively the FCC is auctioning Swiss cheese, where the holes are incumbent licensees with particular rights. These incumbents must either be cleared or worked-around in order for the new entrant to provide a service. Negotiations between the new entrant and the incumbent are often difficult due to holdout by the incumbent. A second problem occurs when multiple new entrants benefit from the clearing of a single incumbent; then each new entrant can hope to free-ride on the clearing done by others. These problems often prevent or delay the efficient clearing of the spectrum.

The government can play an important role in adopting rules that promote the efficient clearing of the spectrum by structuring the rules of negotiation appropriately (Cramton et al. 1998). The broadband PCS rule-making is a good example. The FCC adopted rules that went a long way in minimizing the holdout and free-rider problems that undermine efficient clearing. New licensees were given the right to move an incumbent after a period of time, compensating the incumbent for its relocation costs. This rule minimizes the need for costly negotiations.

The upcoming 700 MHz auction is a more difficult case. This spectrum currently is used for analog television channels 60-69. The spectrum cannot be used for new services until the analog broadcasters terminate over-the-air broadcasting on these channels. Because of the political power of broadcasters, the FCC was unwilling to adopt PCS-type rules that promote efficient clearing. As a result, clearing will be much more costly and inefficient.

### *9.9 Promote market-based tests in spectrum management*

Spectrum auctions are a critical step in the march toward market-based spectrum management. Governments should continue on this path. Flexibility should be the norm, not constraints. Constraints should appear only when those constraints help foster a more competitive environment by adding essential structure. (A good example of the benefits of structure is the success of GSM in Europe.) Specifically, governments should:

- Allow service flexibility
- Allow technical flexibility
- Set initial interference rules, but allow trading
- Set initial geographic and bandwidth scope to an ex ante view of how spectrum will be used, but allow spectrum partitioning and geographic disaggregation
- Eliminate buildout requirements
- Allow transfers of licenses

Many of the current restrictions are holdovers from the days of comparative hearings. These needless regulations should be eliminated. The rate of technological change is now so great that attempting to craft specific regulations as was done in the past is hopeless and destructive. Rather, governments should focus on broad principles that encourage competition. Legislatures especially should refrain from the micro-management of spectrum policy. The complex economic and engineering tradeoffs are much better left to a specialized agency.

## 10 Conclusion

Spectrum auctions represent a huge advance in the way governments allocate scare resources. Despite some early bumps, spectrum auctions largely have succeeded in putting spectrum in the hands of those best able to use it. Economists have made (and continue to make) valuable contributions to spectrum auction design. The simultaneous ascending auction, pioneered by the FCC, has been remarkably successfully in the US and other countries. Its simple process of price discovery promotes efficiency, especially in competitive auctions in which bidders do not have large and varied license synergies. The recent introduction of package bidding to this successful format promises to extend the set of environments where the simultaneous ascending auction performs well.

In most cases, the greatest room for improvement lies not in the auction design, but in the allocation process. Spectrum allocations often are the result of political forces that ignore the underlying economics. Governments would do well to let competitive market forces, not political lobbying, determine spectrum use. The auctioning of spectrum is a major step in the right direction.

# References

Ausubel, Lawrence M. (1997), “An Efficient Ascending-Bid Auction for Multiple Objects,” Working Paper, University of Maryland.

Ausubel, Lawrence M. and Peter Cramton (1999), “The Optimality of Being Efficient,” Working Paper, University of Maryland.

Ausubel, Lawrence M. and Peter Cramton (2001), “The 3G European Auctions,” Working Paper, University of Maryland.

Ausubel, Lawrence M. and Peter Cramton (1996), “Demand Reduction and Inefficiency in Multi-Unit Auctions,” Working Paper, University of Maryland.

Ausubel, Lawrence M., Peter Cramton, R. Preston McAfee, and John McMillan (1997), “Synergies in Wireless Telephony: Evidence from the Broadband PCS Auctions,” *Journal of Economics and Management Strategy*, 6:3, 497-527.

Ausubel, Lawrence M. and Jesse A. Schwartz (1999), “The Ascending Auction Paradox,” Working Paper, University of Maryland.

Ayres, Ian and Peter Cramton (1996), “Deficit Reduction Through Diversity: A Case Study of How Affirmative Action at the FCC Increased Auction Competition,” *Stanford Law Review*, 48:4, 761-815.

Ballard, Charles L., John B. Shoven, and John Whalley (1985), “General Equilibrium Computations of the Marginal Welfare Costs of Taxes in the United States,” *American Economic Review*, 75, 128-138.

Banks, Jeffrey S., John O. Ledyard, and David P. Porter (1989), “Allocating Uncertain and Unresponsive Resources: An Experimental Approach,” *Rand Journal of Economics*, 20, 1-22.

Brusco, Sandro and Giuseppe Lopomo (1999), “Collusion via Signalling in Open Ascending Auctions with Multiple Objects and Complementarities,” Working Paper, New York University.

Bykowsky, Mark M., Robert J. Cull, and John O. Ledyard (2000), “Mutually Destructive Bidding: The FCC Auction Design Problem,” *Journal of Regulatory Economics*, 17, forthcoming.

Chakravorti, Bhaskar, William W. Sharkey, Yossef Spiegel, and Simon Wilkie (1995), “Auctioning the Airwaves: The Contest for Broadband PCS Spectrum,” *Journal of Economics and Management Strategy*, 4, 345-373.

Coase, Ronald H. (1959), “The Federal Communications Commission,” *Journal of Law and Economics*, 2, 1-40.

Cramton, Peter (1995), “Money Out of Thin Air: The Nationwide Narrowband PCS Auction,” *Journal of Economics and Management Strategy*, 4, 267-343.

Cramton, Peter (1997), “The FCC Spectrum Auctions: An Early Assessment,” *Journal of Economics and Management Strategy*, 6:3, 431-495.

Cramton, Peter (1998), “Ascending Auctions,” *European Economic Review*, 42, 745-756.

Cramton, Peter (1998), “The Efficiency of the FCC Spectrum Auctions,” *Journal of Law and Economics*, 41, 727-736.

Cramton, Peter, Robert Gibbons, and Paul Klemperer (1987), “Dissolving a Partnership Efficiently,” *Econometrica*, 55, 615-632.

Cramton, Peter, Evan Kwerel, and John Williams (1998), “Efficient Relocation of Spectrum Incumbents,” *Journal of Law and Economics*, 41, 647-675.

Cramton, Peter and Jesse Schwartz (1999), “Collusive Bidding in the FCC Spectrum Auctions,” Working Paper, University of Maryland.

Cramton, Peter and Jesse Schwartz (2000), “Collusive Bidding: Lessons from the FCC Spectrum Auctions,” *Journal of Regulatory Economics*, 17, forthcoming.

Engelbrecht-Wiggans, Richard and Charles M. Kahn (1995a), “Multi-Unit Auctions with Uniform Prices,” Working Paper, University of Illinois.

Hazlett, Thomas W. (1998), “Assigning Property Rights to Radio Spectrum Users: Why Did FCC License Auctions Take 67 Years?” *Journal of Law and Economics*, 41, 529-576.

Jehiel, Philippe and Benny Moldovanu (2000), “A Critique of the Planned Rules for the German UMTS/IMT-2000 License Auction,” Working Paper, University of Bonn.

Kagel, John H. and Alvin E Roth (1995), *The Handbook of Experimental Economics*, Princeton University Press.

Klemperer, Paul (1998), “Almost Common Value Auctions: The 'Wallet Game' and its Applications to Takeover Battles and Airwaves Auctions,” *European Economic Review*, 42, 757-769.

Klemperer, Paul (2000), “What Really Matters in Auction Design” Working Paper, Oxford University.

Krishna, Vijay and Robert Rosenthal (1997), “Simultaneous Auctions with Synergies,” *Games and Economic Behavior*, 17, 1-31.

Maskin, Eric and John Riley (1984), “Optimal Auctions with Risk Averse Buyers,” *Econometrica*, 52, 1473-1518.

Maskin, Eric and John Riley (1996), “Asymmetric Auctions,” Working Paper, UCLA.

McAfee, R. Preston and John McMillan (1996), “Analyzing the Airwaves Auction,” *Journal of Economic Perspectives*, 10, 159-176.

McMillan, John (1994), “Selling Spectrum Rights,” *Journal of Economic Perspectives*, 8, 145-162.

McMillan, John (1995), “Why Auction the Spectrum?” *Telecommunications Policy*, 19, 191-199.

Milgrom, Paul (1987), “Auction Theory,” in Truman Bewley (ed), *Advances in Economic Theory - Fifth World Congress*, Cambridge, England: Cambridge University Press.

Milgrom, Paul (2000), “Putting Auction Theory to Work: The Simultaneous Ascending Auction,” *Journal of Political Economy*, 108, 245-272.

Milgrom, Paul and Robert J. Weber (1982), “A Theory of Auctions and Competitive Bidding,” *Econometrica*, 50, 1089-1122.

Moreton, Patrick S. and Pablo T. Spiller (1998), “What's in the Air? Interlicense Synergies and Their Impact on the FCC's Broadband PCS License Auctions,” *Journal of Law and Economics*, 41, 677-716.

Perry, Motty and Philip J. Reny (1999), “An Ex-Post Efficient Auction,” Working Paper Penn State University.

Rosenthal, Robert W. and Ruqu Wang (1997), “Simultaneous Auctions with Synergies and Common Values,” *Games and Economic Behavior*, 17, 32-55.

Rothkopf, Michael H., Aleksandar Pekec, and Ronald M. Harstad (1998), “Computationally Manageable Combinatorial Auctions,” *Management Science*, 44, 1131-1147.

Vickrey, William (1961), “Counterspeculation, Auctions, and Competitive Sealed Tenders,” *Journal of Finance*, 16, 8-37.

**EXHIBIT PC-6**

Exhibit PC-6

*Journal of Economics and Management Strategy*, 6:3, 431-495, 1997.

# The FCC Spectrum Auctions: An Early Assessment

Peter C. Cramton*
University of Maryland

*Abstract*

This paper analyzes six spectrum auctions conducted by the Federal Communications Commission (FCC) from July 1994 to May 1996. These auctions were simultaneous multiple-round auctions in which collections of licenses were auctioned simultaneously. This auction form proved remarkably successful. Similar items sold for similar prices and bidders successfully formed efficient aggregations of licenses. Bidding behavior differed substantially in the auctions. The extent of bidder competition and price uncertainty played an important role in determining behavior. Bidding credits and installment payments also played a major role in several of the auctions.

*JEL No.*: D44 (Auctions), L96 (Telecommunications)

*Keywords*: Auctions, Multi-Object Auctions, Spectrum Auctions

Send comments to:
Professor Peter C. Cramton
Department of Economics
University of Maryland
College Park, MD 20742-7211

email: peter@cramton.umd.edu phone: (301) 405-6987

*I am grateful to the National Science Foundation for funding. I served as an auction advisor to several firms (PageNet, MCI, and DCR Communications) and the FCC during this period. The views expressed are my own. I thank Larry Ausubel, Ian Ayres, David Moore, Bob Rosenthal, Greg Rosston, David Salant, and seminar participants for helpful comments. I am especially grateful to Evan Kwerel for many insights and comments.

# The FCC Spectrum Auctions: An Early Assessment

*Table of Contents*

# 1 Introduction

The Federal Communications Commission (FCC) adopted a novel auction form to assign licenses for the next generation of wireless communication services. Up for auction were thousands of Personal Communication Services (PCS) licenses (and other licenses), each covering exclusive rights for a particular slice of the radio spectrum over a geographic area. These licenses, once developed by firms, promise to expand and improve wireless services and increase competition throughout telecommunications.

The licenses were assigned using a simultaneous multiple-round auction. This auction form was proposed by auction experts Paul Milgrom and Robert Wilson of Stanford University and Preston McAfee at the University of Texas. A simultaneous multiple-round auction is similar to a traditional ascending-bid "English" auction, except that, rather than selling each license in sequence, large sets of related licenses are auctioned simultaneously. In every round, a bidder can bid on any of the licenses being offered. The auction does not close until bidding has ceased on all licenses; that is, until a round goes by in which there are no new bids on any of the licenses.

There are three critical features of this method. First, the ascending-bid design allows the bidders to react to information revealed in prior rounds. This reduces the winner's curse, enabling the bidders to bid more aggressively (Milgrom and Weber 1982). Second, by auctioning a large set of related licenses simultaneously, bidders are able to react to prices across licenses. Since bidder valuations depend on the collection of licenses held, providing this price information on related licenses is essential to the formation of efficient aggregations of licenses. Some licenses are complements, whereas others are substitutes. The simultaneous sale of related licenses in an ascending bid auction, gives the bidders the flexibility they need to express these value interdependencies. In addition, it assures that similar licenses sell for similar prices. Third, keeping the bidding on all licenses open until there are no new bids gives the bidders flexibility in switching among license aggregations as prices change.

This paper looks at the first four PCS auctions and two auctions of other licenses to assess the auction's performance in practice. In evaluating the auction design, it should be recognized that efficiency was the primary goal of the FCC, not revenue maximization. The FCC sought to assign the licenses in a timely manner to those firms that will put the licenses to their best use. Fortunately for taxpayers, the goals of efficiency and revenue maximization often coincide. High prices are consistent with an efficient auction, since only bidders with high values are willing to pay high prices. This assumes that the high values are coming from a firm's advantage at providing better services at lower prices, rather than an advantage in restricting market competition. To reduce the chance that high values are derived from more collusive industry structures, the FCC limits the amount of spectrum a firm can hold in any market. Moreover, governments should care about the revenues raised at auction, since auction revenues are less distortionary than the principal source of government revenues — taxation. Ballard, et al. (1985) estimate that the welfare loss from increasing taxes is in the range of 17 to 56 cents per dollar of extra revenue raised. Hence, in designing the auction, the government should be willing to accept some assignment inefficiency if the gain in revenues is sufficiently large.[1]

I find strong evidence that the auction design was successful. The bidding process revealed a great deal of information about likely assignments and relative prices. Bidders were able to react to this information,

---

[1] See Ayres and Cramton (1996) for an analysis on the revenue enhancing effects of bidding credits and installment payments for small bidders in the Regional Narrowband auction. See Rothkopf and Harstad (1990) and Rothkopf, et al. (1996) for a more general analysis.

shifting bids to alternative licenses. The information allowed arbitrage across similar licenses, so prices on similar licenses were close. Finally, the information revealed in the bidding enabled firms to piece together complementary licenses into efficient aggregations.

In order to test and refine the auction design, the FCC wisely chose to begin with the simplest of the auctions: the auction of ten nationwide narrowband PCS licenses. Narrowband licenses are used to provide advanced paging and data services. Because of the narrow bandwidth, they are ill-suited for commercial real-time voice services, like cellular. Cellular services require broadband licenses, which have up to 600 times the bandwidth (30 MHz vs. 50 kHz). Although the nationwide auction is the largest narrowband auction in terms of spectrum offered, it involves the smallest number of licenses and no geographic aggregation issues. However, a bidder can acquire up to three narrowband licenses in any area, so quantity aggregation is an issue. The nationwide auction lasted 47 rounds over five days in July 1994. In the end, the government collected $617 million for the ten licenses. Competition was intense and bidding was aggressive throughout the auction. Cramton (1995) provides a detailed analysis of the nationwide auction from a bidder's perspective.

Next on the block were thirty regional narrowband licenses. Six licenses were sold in each of five regions. Thus, geographic aggregations would play a role, but would be much less complicated than in later auctions, which split the nation into smaller geographic areas, Major Trading Areas (MTAs) or Basic Trading Areas (BTAs). Despite a more rapid start, the auction, conducted in October and November 1994, took 105 rounds to complete. The government raised $395 million. Most of the licenses were sold as nationwide aggregations. Prices were 12.4% higher than in the earlier nationwide auction. In addition, women and minorities won all ten licenses on which they were given a 40% bidding credit. However, competition among the women and minority bidders effectively eliminated the credit: prices were 40% higher on licenses receiving the credit than equivalent licenses without the credit.

These first two auctions were testing grounds for the third and most important spectrum auction, the MTA broadband PCS auction, which began on December 5, 1994 and ended March 13, 1995, after 112 rounds. This was the largest public auction ever. 99 MTA licenses were offered — two 30 MHz licenses in each of 51 MTAs, with the exception of New York, Los Angeles, and Washington in which one of the two licenses in each market was awarded as a Pioneer's Preference (a reward to firms introducing pioneering technologies). Behavior in this auction differed markedly from the narrowband auctions. In particular, the bidding was much more cautious. Bids were mostly at or near the minimum level and a bidder's activity in any round was at or near the minimum activity required to maintain its eligibility. Nonetheless, the auction raised over $7 billion ($7.7 billion including the Pioneer licenses).

In the second broadband auction, the third 30 MHz of spectrum (the C-block) was auctioned as 493 BTA licenses. This auction was for small bidders only. Competition was intense and prices were high — more than double those in the first auction. Attractive payment terms accounted for some of the difference, but differences in competition were also important. The auction raised $10.2 billion in 184 rounds of bidding.

The final two auctions were for licenses that were heavily encumbered. The licenses up for sale were like Swiss cheese. Substantial holes existed where the FCC had previously awarded antenna-based licenses. The first was for Multipoint Distribution Services (MDS), commonly called "wireless cable," since the service is a wireless substitute for standard cable TV. The second, specialized mobile radio (SMR), is used for various wireless applications, such as taxi cab dispatching. Both auctions were competitive. Not surprisingly, incumbents where often successful in acquiring the residual areas of encumbered licenses and usually at a favorable price.

I begin by outlining the design issues. Then I discuss the auction rules (section 3). In section 4, I summarize the experience from the narrowband auctions. Sections 5 and 6 discuss bidding behavior in the MTA and BTA broadband auctions. Section 7 discusses the MDS and SMR auctions. Section 8 assesses the success of the auction design. The reader should be forewarned: this is a descriptive paper about the spectrum auctions. My claims are based only loosely on theory and empirical analysis. Much work remains to be done.

## 2 Auction Design

The design of the PCS spectrum auctions was the result of a rule making process carried out by the FCC from August 1993 to March 1994. Dozens of companies and their auction experts commented on the auction rules in an open public debate. Below I summarize several of the important issues. Although spectrum auction design is discussed elsewhere (McMillan 1994, Milgrom 1995, and Chakravorti et al., 1995), I review the issues here, since understanding the issues will be helpful in assessing the spectrum auctions.

### 2.1 Open Bidding is Better than a Single Sealed Bid

An essential advantage of open bidding is that the bidding process reveals information about valuations. This information promotes the efficient assignment of licenses, since bidders can condition their bids on more information. Moreover, to the extent that bidder values are affiliated, it raises auction revenues (Milgrom and Weber 1982), since the winner's curse is reduced. Bidders are able to bid more aggressively in an open auction, since they have better information about the item's value.

The advantage of a sealed-bid design is that it is less susceptible to collusion (Milgrom 1987). Open bidding allows bidders to signal through their bids and establish tacit agreements. With open bidding, these tacit agreements can be enforced, since a bidder can immediately punish another that has deviated from the collusive agreement. Signaling and punishments are not possible with a single sealed bid.

A second advantage of sealed bidding is that it may yield higher revenues when there are large ex ante differences among the bidders (Maskin and Riley 1995). This is especially the case if the bidders are risk averse (Maskin and Riley 1984, Matthews 1983). In a sealed bid auction, a strong bidder can guarantee victory only by placing a very high bid. In an open auction, the strong bidder never needs to bid higher than the second-highest value.

There was a consensus among experts (many of whom were employed by potential bidders) in favor of open bidding. The advantage of revealing more information in the bidding process was thought to outweigh any increased risk of collusion. Collusion was viewed as unlikely and revenue maximization was a secondary goal.

### 2.2 Simultaneous Open Bidding is Better than Sequential Auctions

A frequent source of debate was whether licenses should be sold in sequence or simultaneously. A disadvantage of sequential auctions is that they limit information available to bidders and limit how the bidders can respond to information. With sequential auctions, bidders must guess what prices will be in future auctions when determining bids in the current auction. Incorrect guesses may result in an inefficient assignment when license values are interdependent. A sequential auction also eliminates many strategies. A bidder cannot switch back to an earlier license if prices go too high in a later auction. Bidders are likely to regret having purchased early at high prices, or not having purchased early at low prices. The guesswork about future auction outcomes makes strategies in sequential auctions complex.

In a simultaneous auction, a large collection of related licenses is up for auction at the same time. Hence, the bidders get information about prices on all the licenses as the auction proceeds. Bidders can switch among licenses based on this information. Hence, there is less of a need to anticipate where prices are likely to go. Moreover, the auction generates market prices. Similar items sell for similar prices. Bidders do not regret having bought too early or too late.

The 1981 sale of rights to use an RCA communication satellite illustrates the practical importance of generating similar prices for similar licenses (McAfee and McMillan 1996). Seven identical licenses were sold in a sequence of ascending bid auctions. Prices ranged from $14.4 million for the first license auctioned to $10.7 million for the sixth. The bidder with the $14.4 million winning bid petitioned the FCC to throw out the auction, because the auction procedure violated common carrier nondiscrimination rules. The FCC agreed and required RCA to charge the same price to all bidders.

Proponents of sequential auctions argue that the relevant information for the bidders is the final prices and assignments. They argue that simultaneous auctions do not reveal final outcomes until the auction is over. In contrast, the sequential auction gives final information about prices and assignments for all prior auctions. This final information may be more useful to bidders than the preliminary information revealed in a simultaneous auction.

Supporters of sequential auctions also point out that the great flexibility of a simultaneous auction makes it more susceptible to collusive strategies. Since nothing is assigned until the end in a simultaneous auction, bidders can punish aggressive bidding by raising the bids on those licenses desired by the aggressive bidder. In a sequential auction, collusion is more difficult. A bidder that is supposed to win a later license at a low price is vulnerable to competition from another that won an earlier license at a low price. The early winner no longer has an incentive to hold back in the later auctions.

A final advantage of a sequential auction is that it has been used extensively in practice and is easier to implement than a simultaneous auction. A sequence of oral auctions can be done quickly with little risk of failure. Adopting an unproven design, like the simultaneous auction, exposes the FCC to political embarrassment should the auction fail.

In the end, the advantages of simultaneous auctions won out. Decision makers at the FCC were convinced that the virtues of the simultaneous auction — greater information release and greater bidder flexibility in responding to information — would improve efficiency. Although the FCC was concerned that a simultaneous auction might be more collusive, it felt that the setting was otherwise not conducive to collusion. In any event, sequential auctions would not eliminate the possibility for collusion.

The ability to successfully implement a novel auction form was a chief concern. However, the FCC was able to test and refine the simultaneous auction in the simpler and lower stake setting of narrowband licenses. In addition, experimental tests of the design were conducted before the first narrowband auction began. Tests were conducted at CalTech's experimental lab by Charles Plott, David Porter, and John Ledyard. Several large bidders conducted their own tests as well. These tests provided evidence that the design would work in practice.

### 2.3 Package Bids are too Complex

A bidder's value of a license may depend on what other licenses it wins. Philadelphia may be worth more to a bidder if it wins the adjacent licenses in New York and Washington. Hence, bidders may value being able to bid on a combination of licenses, rather than having to place a number of individual bids. With a package bid, the bidder either gets the entire combination or nothing. There is no possibility that the bidder will end up winning just some of what it needs.

With individual bids, bidding for a synergistic combination is risky. The bidder may fail to acquire key pieces of the desired combination, but pay prices based on the synergistic gain. Alternatively, the bidder may be forced to bid beyond its valuation in order to secure the synergies and reduce its loss from being stuck with the dogs. This is the exposure problem. Individual bidding exposes bidders seeking synergistic combinations to aggregation risk.

Not allowing package bids can create inefficiencies. For example, suppose there are two bidders for two adjacent parking spaces. One bidder with a car and a trailer requires both spaces. She values the two spots together at $100 and a single spot is worth nothing; the spots are perfect complements. The second bidder has a car, but no trailer. Either spot is worth $75, as is the combination; the spots are perfect substitutes. Note that the efficient outcome is for the first bidder to get both spots for a social gain of $100, rather than $75 if the second bidder gets a spot. Yet any attempt by the first bidder to win the spaces is foolhardy. The first bidder would have to pay at least $150 for the spaces, since the second bidder will bid up to $75 for either one. Alternatively, if the first bidder drops out early, she will "win" one license, losing an amount equal to her highest bid. The only equilibrium is for the second bidder to win a single spot by placing the minimum bid. The outcome is inefficient, and fails to generate revenue. In contrast if package bids are allowed, then the outcome is efficient. The first bidder wins both licenses with a bid of $75 for both spots.

The inefficiency in this example does not rely on there being full information about values. If values are privately known, then the first bidder will decide to bid for the pair only if it is sufficiently likely that the second bidder has a low value. Otherwise the exposure is too great and the first bidder will not participate.

This example is extreme to illustrate the exposure problem. The inefficiency involves large bidder-specific complementarities and a lack of competition. In the PCS auctions, the complementarities are less extreme and the competition is greater.

Unfortunately, allowing package bids creates other problems. Package bids may favor bidders seeking large aggregations due to a variant of the free-rider problem, called the threshold problem (Bykowsky, et al. 1995). Continuing with the last example, suppose that there is a third bidder who values either spot at $40. Then the efficient outcome is for the individual bidders to win both spots for a social gain of 75 + 40 = $115. But this outcome may not occur when values are privately known. Suppose that the second and third bidders have placed individual bids of $35 on the two licenses, but these bids are topped by a package bid of $90 from the first bidder. Each bidder hopes that the other will bid higher to top the package bid. The second bidder has an incentive to understate his willingness to push the bidding higher. He may refrain from bidding, counting on the third bidder to break the threshold of $90. Since the third bidder cannot come through, the auction ends with the first bidder winning both spaces for $90.

A second problem with allowing package bids is complexity. If all combinations are allowed, even identifying the revenue maximizing assignment is an intractable integer programming problem when there are many bidders and licenses. The problem can be made tractable by restricting the set of allowable combinations (Rothkopf, et al. 1995). However, these restrictions may eliminate many desirable combinations, especially in broadband PCS where cellular holdings and other existing infrastructure tend to create idiosyncratic license synergies. Alternatively, a bid mechanism can be used that puts the computational burden on the bidders. In the AUSM system, bidders must propose bids that in combination with other bids exceed the amount bid for standing package bids (Banks, et al. 1989).

Increased complexity is a legitimate concern when considering package bids. Although simultaneous auctions with package bids were successfully used in the laboratory (Bykowsky, et al. 1995), it was far from certain that the FCC could successfully run auctions with package bids under the tight time schedule. Furthermore, allowing package bids would weaken a central advantage of auctions: transparency. A bidder who offered a higher bid for part of a combination might be unable to see why it lost.

The FCC decided against allowing package bids. The threshold problem and increased complexity of package bids were thought to be worse than the exposure problem.

### 2.4 Other Issues

Having settled on a simultaneous ascending-bid auction without package bids, several issues of implementation remained.

How much information should the bidders be given? The insights from Milgrom and Weber (1982) suggest that typically more public information is better. Hence, with the exception of bidder identities in the nationwide auction, the FCC decided to reveal all information: the identities of the bidders, all the bids, and the bidders' current eligibility. So long as collusion and predatory bidding are not problems, revealing more information should improve efficiency and increase revenues. It also makes for a more open process.

Should the rounds be discrete or continuous? The FCC decided on discrete rounds, which would give the bidders a specific amount of time to respond to bids. Continuous bidding has the advantage that it makes endogenous the time between bids. Bidders can respond quickly when the strategic situation is simple, and take more time when it is complex. Discrete bidding is easier to implement and it gives the bidders a specific schedule to follow. Bidders know exactly when new information will be available and when they have to respond.

How can the FCC best control the pace of the auction? There are three key instruments: the frequency of rounds, the minimum bid increments, and an activity rule, which sets minimum levels of bidding activity. These are discussed later.

## 3 Auction Rules

The basic rules for the auctions are the same. A group of licenses with strong value interdependencies are up for auction at one time. A bidder can bid on any collection of licenses in any round, subject to an activity rule which determines the bidder's current eligibility. The auction ends when a round passes with no new bids on any license. This auction form was thought to give the bidders the greatest flexibility in expressing values and building license aggregations. An auction winner gains the exclusive right to use the spectrum in accordance with FCC rules for a period of ten years. Licenses typically are renewed with a negligible charge provided the licensee has adhered to FCC rules and met buildout requirements. Licensees at any time may resell licenses purchased without special preference. Resale of licenses purchased with special preference is restricted to prevent “unjust enrichment.”

Within this basic structure, some of the details differ among the auctions. Here I mostly focus on the MTA broadband rules. Detailed auction rules for the narrowband auctions are given in the FCC's Third Report and Order (1994); the rules for the broadband auctions are given in the Fifth Report and Order (1994). Refinements were made in subsequent public notices and orders on reconsideration.

**Quantity Restrictions.** To promote competition, a firm is limited in the quantity of spectrum it can hold in any market. For narrowband spectrum, a firm can hold no more than three licenses in any market. For broadband auctions, firms can hold no more than 45 MHz of commercial mobile radio service (CMRS) spectrum in any area. PCS and cellular are classified as CMRS spectrum. Hence, a cellular incumbent (a 25 MHz license) is ineligible to bid for a 30 MHz license in its service area. This assures that each 30 MHz license in every market will be held by distinct firms, independent of the two cellular incumbents.

**Designated Entities.** To encourage broad participation in wireless communications, designated firms (women, minorities, and/or small businesses) were given bidding credits on specific licenses. These credits, ranging from 10% to 40%, were intended to offset any disadvantage these firms faced in raising capital and providing services. Designated firms often were eligible for attractive installment payment plans also. No preferences were given in the MTA broadband auction. However, in the C-block auction, only entrepreneurs (annual revenues less than $125 million) and small businesses (annual revenues less than $40 million) were eligible to bid.

**Payment Rules.** Payments are received by the FCC at three times: (1) An upfront payment before the bidding begins assures that the bidder is serious. Any withdrawal penalties are taken from the bidder's upfront payment.[2] (2) A down payment of 20 percent is paid within five business days after the close of the auction. (3) A final payment of the remaining 80 percent is paid within five business days of the award of the license. Firms eligible for installment payments have a reduced down payment and make quarterly payments over 10 years. Licenses are awarded one to three months after the auction.

The upfront payment, due two weeks before the auction begins, defines the bidder's maximum eligibility in any round of bidding. Each bidder must make an upfront payment of $.02 per MHz-pop for the largest combination of licenses the bidder intends to be active on in any round. The size of a PCS license is measured in MHz-pop: the bandwidth in megahertz times the population in the license area. A bidder is active on a license if it places a valid bid or was the high bidder on the license in the prior round. Thus, an upfront payment of $6 million in the broadband auction would make a bidder eligible to be active on licenses covering $6/(30 \cdot .02) = 10$ million people. The upfront payment is not license specific; it simply limits total bidding activity in any round.

**Minimum Bid Increments.** To assure that the auction concludes in a reasonable amount of time, the FCC specifies minimum bid increments between rounds. Initially, bid increments are set at the greater of 5% or $.02/MHz-pop. Before a license receives a bid, the minimum bid is 0. Bid increments are adjusted in response to bidder behavior. In the early rounds, when bid activity is high, the FCC sets larger bid increments; in the later rounds, when bid activity is low, the FCC sets smaller bid increments.

**Activity Rule.** The activity rule is a further device for controlling the pace of the auction. It forces a bidder to maintain a minimum level of activity to preserve its current eligibility. As the auction progresses, the required activity increases in stages. There are three stages in the activity rule proposed by Paul Milgrom and Robert Wilson. In the initial stage each bidder must be active on at least one-third of its current eligibility. Activity is measured as the sum of the MHz-pops on which the bidder submitted a valid bid or was the high bidder. If activity falls below the one-third level, then the bidder's current eligibility is reduced to three times its current activity. In stage 2, a bidder must be active on at least two-thirds of its current eligibility. If its activity falls below the two-third level, the bidder's current eligibility is reduced to 1.5 times

---

[2] The importance of significant upfront payments is illustrated by the Interactive Video Data Services (IVDS) auction, held on July 27-28, 1994. This auction was marred by several defaults. Upfront payments were only $500 per license for licenses valued in excess of one million dollars. Defaults occurred on 114 of 574 licenses. The defaults came from a handful of speculators that apparently did not understanding the rules or the technology before the auction. A large upfront payment, which serves as a deposit to ensure payment of a penalty in the event of default, provides an incentive for bidders to be well-prepared.

its current activity. In stage 3 of the auction, a bidder must be active on 100 percent of its current eligibility. If its activity falls below 100 percent, the bidder's current eligibility is reduced to its current activity.

A waiver prevents a reduction in eligibility in the event of bidder error or some other problem. Bidders are given five waivers. (In the regional auction each bidder was given one waiver per stage.) Waivers are applied automatically. An automatic waiver is used whenever a bidder's eligibility would otherwise fall as a result of its reduced bid activity. A bidder that does not wish to maintain its eligibility from the prior round may override the automatic waiver.

**Number of Rounds per Day.** A final means of controlling the pace of the auction is the number of rounds per day. In the narrowband auctions, many rounds were conducted each day. This made sense given the relatively small number of licenses and more modest stakes. The time between rounds was longer early in the auction (about 2 hours), but shortened toward the end when bidding activity was low and strategies were simple. At the end of the nationwide auction, rounds were occurring every 20 minutes. In the MTA auction, the number of rounds per day was much less. Initially only one round was conducted per day. After the first week, typically two rounds were conducted each day.

**Stopping Rule.** A simultaneous stopping rule is used to give the bidders maximum flexibility in pursuing backup strategies. All markets close if a single round passes in which no new bids are submitted on any license. In the MTA auction, the FCC retained the right to keep the auction open if there were no new bids in a round. This prevents a premature close of the auction at the end of stages 1 and 2 if bidders simply are bidding to maintain eligibility. It also allows the FCC to use a larger bid increment. If the increment chokes off activity, then the FCC can drop the increment and/or move to the next stage in order to restore bid activity.

**Bid Information.**[3] Each bidder is fully informed about the identities of the bidders, the size of the upfront payments, and which bidders qualify as designated entities. High bids and bidder identities are posted after each round. In addition, all valid bids and bidder identities are displayed at the conclusion of each round, together with each bidder's eligibility and waivers.[4]

**Bid Withdrawal.** After the close of each round, there is a brief withdrawal period in which the high bidders can withdraw their bids subject to a bid withdrawal penalty. If a bidder withdraws its high bid, the FCC is listed as the high bidder and the minimum bid is the second-highest bid for that license. The second-highest bidder is in no way responsible for the bid. If no firm bids on the license, the FCC can reduce the minimum bid. Typically, the FCC drops the minimum bid only one or two times, before committing not to reduce the minimum bid further. A withdrawn high bid counts as bidding activity for the high bidder in the round the bid is withdrawn. This enables the bidder to switch licenses without losing eligibility.

To discourage insincere bidding, there are penalties for withdrawing a high bid. The penalty is the larger of 0 and the difference between the withdrawn bid and the final sale price. This penalty is consistent with the standard remedy for breach of contract. The penalty equals the damage suffered by the FCC as a

---

[3] Readers can obtain the bidding data for all of the auctions by anonymous ftp at ftp.fcc.gov. For the last four auctions, tracking tools created by the author are also available. These tools enable the user to analyze the bidding data within a spreadsheet environment. See the FCC's Web site at www.fcc.gov.

[4] In the nationwide auction, bidder identities were not disclosed. It was thought that concealing identities might reduce the chance of predatory bidding (bidding to raise rivals' costs) and collusion. However, concealing identities was largely unsuccessful, and predatory bidding and collusion were not problems (Cramton 1995); hence, the decision to reveal identities in subsequent auctions.

result of the withdrawal. If the bidder defaults or is disqualified after the close of the auction, the penalty is increased by 3% of the eventual sale price to compensate the FCC for additional selling costs. The additional 3% default payment is also intended to discourage defaults (after the auction closes) relative to withdrawals (during an auction).

## 4 The Narrowband Experience

The nationwide and regional narrowband auctions served two important roles. First, the auctions assigned narrowband spectrum, allowing winning firms to begin offering advanced paging services. Second, they provided an opportunity to test and refine the rules for the all important MTA broadband auction. In this section, I summarize the bidding behavior in the narrowband auctions and its implication for the broadband auction.

### 4.1 Nationwide Narrowband PCS Auction

Up for auction were ten nationwide licenses in three different types: 50/50 kHz paired licenses (50/50s), 50/12.5 kHz paired licenses (50/12s), and 50 kHz unpaired licenses (50s). With the “paired” licenses, the first number denotes the amount of outbound capacity (from network to consumer) and the second number denotes the amount of inbound capacity (from consumer to network). An unpaired license consists of only outbound capacity. Inbound bands are not the same as outbound bands, because of differing power constraints. Hence, one 50/50 kHz paired license is not the same as two 50 kHz unpaired licenses. There are five 50/50s (blocks 1 to 5), three 50/12s (blocks 6 to 8), and three 50s (blocks 9 to 11). License 9 was not up for auction because it had been set aside for Mtel as a Pioneer's Preference award. Women and minorities were given a 25% bidding credit on one license of each type (blocks 5, 8, and 11).

The auction began July 25, 1994 and concluded July 29, after 47 rounds. Of the 29 bidders that submitted upfront payments, four bidders failed to show up at the auction. Eight more bidders dropped out in the first round, leaving 17 bidders competing for the 10 licenses. In the end, licenses were won by six firms, as shown in Table 1. Price is stated in \$/MHz-pop (i.e., the cost of the license in dollars divided by the product of the size of the license in megahertz and the population covered, which is 253 million for a nationwide license). This makes prices among license types comparable. One remarkable aspect of the outcome is that the final prices for all the licenses were nearly equal at about \$3.10 per MHz-pop. Within a license type, prices were nearly identical.

Bidders were able to form efficient aggregations. Those winning multiple licenses (PageNet and McCaw) acquired adjacent bands. Owning adjacent bands increases the firm's capacity, since it can use the guard band, which separates adjacent bands, for transmission. Otherwise, the guard band must be clear to prevent interference between adjacent bands.

Figure 1 displays the auction revenue and a measure of bid activity (the percent of new bids) in each round. Revenues increased rapidly early in the auction when bid activity was high. As prices increased, bid activity declined as did the rate of increase in revenues. Bidding was aggressive throughout the auction. Indeed, minimum bid increments proved unimportant. Bidders routinely bid well in excess of the minimum. The activity rule also played no role. The auction never left stage 1. The FCC felt the auction was progressing sufficiently quickly, so that stage 2 was not needed.

None of the three licenses with the designated entity (DE) bidding credit were won by designated entities. A 25% bidding credit was insufficient to attract sufficient DE capital to win a license. One explanation is that the designated entities were surprised by and unprepared for the high prices. Indeed, most of the DEs dropped out in the first round of the auction.

There was a tendency for the bidding to move down from the larger licenses (50/50s and 50/12s) and then to the smaller licenses (50s). Through the first 18 rounds, bidding was primarily on the 50/50s and 50/12s. After round 19, bidding stopped for 7 rounds on the 50/50s, but then resumed again in round 26, before concluding in round 37. Bidding on the 50/12s was heavy throughout the first half of the auction, but concluded in round 25, 21 rounds before the end of the auction. Bidding on the 50s was light and steady throughout the auction. The last 9 rounds of the auction involved new bids on only the 50s. In the final eight rounds, there was just a single new bid in each round — three bidders were competing for two licenses.

Jump bidding — the act of raising a high bid by much more than the minimum increment — was pervasive throughout the auction. 49% of all new high bids were jump bids that exceeded the high bid by more than two bid increments. 23% of these jump bids were raises of one's own high bid (bidders anticipating a raise by a rival). Even in the opening round, with minimum bids between \$250,000 and \$500,000, bidding started at \$20 million on two licenses and \$10 million on five others. The \$20 million opening exceeded the minimum bid by a factor of 40. This behavior seems to fly in the face of common bidding wisdom. However, there may be good reasons for jump bidding, especially in an auction where the aggregation of licenses plays a role. The basic idea is that the jump bid may convey information about a bidder's valuations. It is a message of strength, conveying that the bidder has a high value for the particular license. Jump bidding has a cost — it exposes the bidder to the possibility of leaving money on the table. It is precisely this cost that makes the communication credible. A bidder with a low value would not find it in its interest to make a large jump. The gain, increasing the chance of winning the license, would not exceed the cost, the risk of overbidding. It is not enough for a bidder to simply announce, “I have a high value. You had better look elsewhere.” All bidders, high value and low value alike, have an interest in making such a statement. To make the statement credible the words must be backed up by an action that a low value bidder would find too costly.

Signaling a high value is a good thing for a bidder to the extent it gets rivals to look elsewhere. This may be the case if there are strong synergies among licenses. A bidder's confidence about the chance it can form a desirable aggregation should fall if it is convinced a rival has a high value. However, the cost of staying in may be zero for a bidder looking for a single license. For the most part, jump bidding appeared not to discourage firms from bidding. Avery (1994) provides an equilibrium analysis of jump bidding in a common value setting.

The simultaneous multiple-round auction was remarkably successful in this first PCS auction. Competition was intense, similar items sold for similar prices, and aggregations appeared efficient. Interestingly, the bid increments and activity rules proved unimportant. Firms bid aggressively and were rarely constrained by bid increments or activity rules.

### 4.2 Regional Narrowband PCS Auction

This auction was of special interest, because it used rules that were nearly identical to the rules in the MTA broadband PCS auction. Although these rules were used in the nationwide auction, the nationwide auction did not allow the possibility for forming geographic aggregations. In the regional auction, the formation of geographic license aggregations was critical. Hence, the regional auction gave us a first glimpse of bidding behavior designed to form large geographic aggregations.[5]

---

[5] See Ayres and Cramton (1996) and Milgrom (1995) for analysis of the regional auction.

The regional narrowband PCS auction began on October 26, 1994, and ended on November 8, after 105 rounds. Initially, there were 28 bidders competing for the 30 regional licenses. Six bands (two 50/50s and four 50/12s) were offered in each of five regions. In the end, nine firms won licenses. Table 2 indicates the final outcome. Prices ended 12.4% above the prices in the nationwide auction. Most of these regional licenses went to firms with a nationwide strategy (PageMart, PCS Development, Mobile Media, Advanced Wireless, and AirTouch). Figure 2 tracks the progress of the auction round by round. After the first six rounds, it was a much slower auction than the nationwide auction.

The first round of the auction set the stage for an early escalation in prices. PCS Development opened with bids totalling $80 million ($48 million net of the DE credit) for a nationwide aggregation of 50/50s, matching the final price from the nationwide auction. Clearly the information revealed in the nationwide auction played a role in the regional auction. PageMart opened with two nationwide bids of $32 million on the 50/50s, as well as two nationwide bids on the 50/12s. Mobile Media opened with three nationwide bids of $20 million each on a 50/50 and two 50/12s. Most of the other bidders were more cautious. Forming a nationwide aggregation clearly was important for several bidders.

By round 7, the assignment of licenses was quite close to the final assignment reached nearly 100 rounds later. PageMart, PCS Development, Mobile Media, and Advanced Wireless each had staked out a nationwide aggregation on blocks 1 to 4, respectively. AirTouch apparently wanted licenses in three regions. The biggest disagreement was on the 50/12 DE block. Both Shearing and Benbow were fighting for a nationwide aggregation. Prices increased by about 40% over the final 96 rounds on bidding activity sparked by the excess demand of DE bidders. As in the nationwide auction, predictions of a rapid end of the regional auction proved false. The long end is partly explained by the greater number of licenses and substitution possibilities, and partly by the use of a 2% bid increment after round 20, rather than 5%. However, since many rounds were conducted each day, the use of this smaller increment extended the auction less than one week.

Unlike in the nationwide auction, the regional auction involved three stages of bidding. Stage 2 began in round 21 (a bidder must be active on two-thirds of its current eligibility). Since most bidders were bidding aggressively in stage 1, the move to stage 2 had little effect. There was a modest increase in activity for a few rounds. Stage 3 began in round 74 (a bidder must be active on 90% of its current eligibility). Bidding activity picked up slightly. Mostly this was caused by 50/12 bidders keeping the 50/50 option open by bidding on two 50/12s, rather than one.

Also unlike in the nationwide auction, bid withdrawals were observed in the regional auction. In round 78, PCS Development withdrew its bid of $18 million on block 6 in the Western region. The final selling price was $18.2 million, so no penalty was incurred. The withdrawal was the result of strategic bidding, not a shift in license aggregations. PCS Development's bid on block 6 was an attempt to punish Shearing for repeated bidding on block 2, which PCS Development wanted as a nationwide aggregation. The only other withdrawal occurred in round 83 when PageMart withdraw its bid of $10.129 million on block 5 in the Southern region and shifted to blocks 3 and 4. The final selling price was $8 million, so PageMart incurred a withdrawal penalty of $2.129 million. This withdrawal also was due to strategic bidding. PageMart needed to bid on two 50/12s to maintain eligibility so that it could return to the 50/50 license in block 2 if prices on the 50/12s increased too much. Apparently PageMart reasoned that it was better to bid against the nationwide aggregations of Mobile Media (block 3) and Advanced Wireless (block 4). Winning these licenses would mean success in breaking up two nationwide competitors. At worst, the bids would raise the costs of PageMart's nationwide competitors and enable a move up to the 50/50. Perhaps PageMart thought that someone might be willing to pick up the 50/12 on block 5 at the withdrawal price. However, it was too late in the auction. The block 5 50/12 was not picked up until the FCC dropped the minimum price to $8 million (from $9.93 million). At this price InstaCheck was willing to move off the Northeast license, ending the auction.

A remarkable feature of the regional auction was the role designated entity bidders played in determining prices. All DE licenses were sold to DEs. Of the 28 bidders, 20 had some kind of DE preference. Nearly one-half of the upfront payments came from DE bidders. Competition among the DEs was so intense that the 40% bidding credit was entirely bid away. DE bidders paid roughly the same net prices as non-DE bidders. The effective DE discount on block 2 was 1.8% and the discount on block 6 was -2.2%.

This was in stark contrast to the outcome in the nationwide auction in which the DEs dropped out early, most after the first round of bidding. The difference in outcome was largely due to changes in the DE rules. Although the increase in the bidding credit from 25% to 40% was the most obvious change, it probably was unimportant. Either credit would have kept non-DE bidders out of the DE licenses. Hence, it was competition among DEs that determined prices on the DE licenses, rather than competition between DE and non-DE bidders. Two other changes were critical. First, allowing installment payments for DE bidders at attractive terms (10-year Treasury rate) solved one of the major problems DEs face — the raising of capital. Second, the definition of women and minority controlled firms was relaxed. In the nationwide auction, 50.1% equity ownership by women/minorities was required. In the regional auction, 25% equity ownership was sufficient as long as the women/minorities had voting control and no other investor owned more than 25%. This made it easier for DE firms to partner with existing paging companies, which solves the second major problem facing DE bidders: acquisition of technical knowledge. Each of the bidders winning DE licenses partnered with one or more established paging companies. PCS Development partnered with A-Plus, Arch, and USA Mobile; Benbow partnered with Westlink; and Shearing partnered with Adelphia. These partnerships brought essential knowledge in addition to capital to the DE firms. As a result, these DE bidders did not look much different from the non-DEs. A third important factor in the success of the DEs was that much of the uncertainty about prices was resolved in the nationwide auction. DE bidders had the time and the knowledge to adequately prepare for the regional auction.

One of the puzzles in the regional auction was that prices were 12.4% higher than in the nationwide auction. Evidence from wine auctions suggests that, when similar items are sold in sequence, the later items tend to sell for less than the early items. This is known as the “declining price anomaly” (Ashenfelter 1989, McAfee and Vincent 1993).[6] One explanation for the rise in prices is the more favorable DE rules. These rules, which were not known at the time of the nationwide auction, brought more capital to the auction and effectively reduced the supply of non-DE licenses. This reduction in supply raised prices for the non-DE bidders. Moreover, competition among DE bidders was so strong that the DE bidders crossed over to the non-DE licenses, raising the revenues from non-DE licenses by more than $50 million (Ayres and Cramton 1996). The favorable treatment of DE bidders had the effect of increasing auction revenues. Such a conclusion is consistent with auction theory. When bidders are asymmetric ex ante, the revenue maximizing auction will tend to favor the weak bidders (Myerson 1981, McAfee and McMillan 1987). By favoring the weaker party, the weaker party can compete more effectively with the strong firms. This heightened competition tends to raise prices.

An alternative explanation for the higher prices in the regional auction is that competition was greater

---

[6] There are exceptions to declining prices. Gandal (1995) finds that prices tended to increase in the sequential sale of Israeli cable television licenses. Apparently firms were willing to pay more for later licenses, because of complementarities.

because of the presence of several bidders with regional strategies. However, since most regional licenses were sold as nationwide aggregations, many of the winning firms in the regional auction could have purchased in the nationwide auction, reducing prices in the regional auction.

Another explanation for the higher prices in the regional auction is that, because of the obvious interest in single-band nationwide aggregations, firms were able to impose costs on competitors by bidding on a piece of a competitor's nationwide aggregation. There is some evidence of such predatory bidding.

The regional auction made clear that it is possible for firms to form large aggregations in a simultaneous multiple-round auction. Moreover, it showed that the nationwide prices were no fluke and that DE preferences could have pronounced effects on competition and outcomes. Although the activity rule continued to be of little importance in this auction, low bid increments did lengthen the end of the auction.

## 5 MTA Broadband PCS Auction

On December 5, 1994, the first and most important broadband PCS auction began. One-half of the 120 MHz of broadband spectrum was on the block: two 30 MHz licenses (bands A and B) in each of 51 MTAs, less the three Pioneer's Preference awards (the A license in New York, Los Angeles, and Washington). The 51 MTAs range in size from New York with 26.4 million people to American Samoa with 47 thousand people. The ten largest MTAs cover 50% of the population. The two narrowband auctions, allocating just 1.2 MHz of spectrum, were small compared to the 60 MHz allocated in the MTA broadband auction. Competing in the auction were some of the largest telecommunication companies in the world, as well as many smaller firms. There were no benefits to designated entities. Benefits to DEs would come in later auctions when the remaining 60 MHz of spectrum is sold. The auction ended on March 13, 1995 after 112 rounds and three months of bidding. The government collected over $7 billion ($7.7 billion including the Pioneer payments).[7]

### 5.1 The Rush for Alliances

To be eligible to bid, a bidder had to submit a Short Form Application by October 28, 1994. The Short Form specified all alliances and listed the licenses on which the firm wished to bid. All partnering had to occur by October 28. The FCC allowed alliances, because they might be essential to efficiency. For example, a nationwide service might be efficient, due to marketing advantages, but no individual firm may have the resources to bid for one. On the other hand, alliances may reduce efficiency by limiting competition in the auction. During the two weeks before the deadline, there was a frenzy of activity in forming alliances. The largest telecommunication companies in the world were engaged in a last-minute dance to form alliances that would shape the future of PCS and have far reaching implications throughout telecommunications.[8]

---

[7] The Pioneer's Preference winners pay for their licenses according to a formula in the GATT legislation. Each pays the greater of $7.50/pop or 85% of the unweighted per pop price in the top-23 markets excluding New York, Los Angeles, and Washington. The formula was included as an amendment to GATT to make the legislation revenue neutral.

[8] Bidders were allowed to form alliances during the auction, but only with bidders applying for a disjoint set of licenses. This option was not used by any of the bidders. It only works with bidders with very focused interests - those applying for only a few licenses. But bidders with focused interests have little to gain by forming alliances with bidders outside their interests.

In the end, two large alliances formed: WirelessCo, a limited partnership between Sprint (40%) and three large cable companies: TCI (30%), Comcast (15%), and Cox (15%); and PCS PrimeCo, a collection of three Bell Operating Companies (BOCs) (Bell Atlantic, Nynex, and USWest) and AirTouch, the wireless spinoff of PacTel. The four companies in PrimeCo first got together as pairs: USWest-AirTouch and Bell Atlantic-Nynex. Each firm has a 25% stake in PrimeCo. The alliance was in part prompted by a desire by the Bell Atlantic-Nynex pair to secure Los Angeles. There appeared to be a consensus in the industry that PacTel would win the only available license in Los Angeles. Cox held the other as a Pioneer's Preference award, and was already aligned with WirelessCo. Hence, Bell Atlantic-Nynex apparently felt that their best way to get coverage in Los Angeles was to partner with either PacTel or USWest-AirTouch. AirTouch held one of the two cellular licenses in Los Angeles.

These alliances were significant because they greatly reduced eligibility. Since bidders could not bid in any market in which they hold a significant cellular interest, joining forces with a large cellular provider reduced eligibility. Firms had a double incentive to join. First, merger would enable the firms to serve a larger geographic area, perhaps near-nationwide, which has many advantages for marketing. Consumers value seamless roaming and national advertising campaigns then can be used. Second, merger reduces the number of bidders and the bidders' eligibility. Any merger that includes the marginal bidder (the bidder with the third-highest value) reduces the price paid.

The WirelessCo merger likely increased competition by combining complementary assets: long distance, national marketing, and local cable networks. Neither Sprint, nor the cable companies, were well positioned to go it alone, but together they represented a strong force. Moreover, since none of the firms had sizeable cellular holdings, the alliance made WirelessCo ineligible to bid on only 17% of the population.

In contrast, the PrimeCo alliance reduced competition in the auction. The BOCs and AirTouch all had sufficient capital to form substantial aggregations independently. By joining forces, the number of deep-pocketed bidders was reduced as was total eligibility. PrimeCo was excluded from bidding on 64% of the population as a result of the cellular holdings of its members. Hence, the alliance eliminated three deep-pocketed bidders in nearly two-thirds of the U.S. and turned four bidders into one in the remaining third.

Finally, AT&T's acquisition of McCaw Cellular for $11.5 billion meant that AT&T would be ineligible to bid on licenses covering 48% of the population.

Although 62 bidders submitted short form applications for the auction, only 30 followed through with upfront payments. The upfront payments totalled $522 million. The largest ($118 million for 197 million pops of eligibility) was from WirelessCo. Four firms put up the minimum upfront payment of $28 thousand, enough to bid on American Samoa.

One consequence of the two major alliances was a reduction in total eligibility. This auction began with an eligibility ratio (total eligibility in pops divided by total pops being auctioned) of 1.93. The eligibility ratios in the narrowband auctions were several times this amount. The eligibility ratio in the nationwide auction was 8.8 and was 6.1 in the regional auction. Some potential bidders with limited capital probably were scared off by the thought of bidding against the likes of AT&T and PrimeCo. At least one bidder, Craig McCaw, bidding as Alaacr Communications, recognized that prices might be low in some markets. McCaw reasoned that there were few large bidders and in many markets two or more of the largest firms were excluded from bidding because of cellular ownerships. Hence, McCaw decided at the last moment to participate. In deference to his former employees at McCaw Cellular (now part of AT&T), McCaw applied for every license that AT&T did not apply for.

Three of the firms, WirelessCo, AT&T, and PrimeCo, went into the auction with a nationwide strategy. Each firm wanted to fill the holes in its cellular network. Other firms had focused geographic interests.

PacTel, for example, announced its intent to win Los Angeles and San Francisco, although it applied for all licenses. Ameritech was only interested in two midwest licenses. GTE was interested in a handful of licenses that would work well with its existing network. Several firms applied for just a single license, making a clear statement about their intent. In contrast, McCaw was looking for value wherever it might be.

One of the major differences between this auction and the narrowband auctions was the extent of ex ante asymmetries among the firms. Values in broadband PCS are closely related to the network infrastructure the firm already has in place. This geographic heterogeneity together with the much smaller geographic markets means that in many instances the firms have a good idea who the high valuers are likely to be in many markets. PacTel has high values in Los Angeles and San Francisco; Ameritech has high values in Cleveland and Indianapolis; AT&T has high values in Washington and Chicago; PrimeCo has high values in Chicago and Dallas. If the known differences are large, it is possible that at least in some markets, the assignment will be resolved without using price to drive away bidders with lower values. If all the bidders know that PacTel has the highest value in Los Angeles, there is less incentive for a bidder to bid against PacTel in Los Angeles. The bidder may succeed only in driving prices higher. The smaller geographic licenses make the possibility of tacitly dividing up the licenses a greater possibility. Not only can the pie be divided along dimensions of perceived value, but punishments can be directed at defectors. For example, PacTel is easily punished for bidding outside of California. A bidder simply tops PacTel's high bid in Los Angeles. Still such tacit collusion is upset by a few value-seeking bidders with deep pockets that do not have clearly specified geographic interests. They have little reason to cooperate and are difficult to punish. However, bidding by these value-seeking bidders may be limited by budget constraints and a lack of existing infrastructure.

### 5.2 Bidding Behavior

Bidding behavior in the MTA auction was dramatically different from that in the narrowband auctions. The bidding was consistently restrained and cautious. Bids were rarely much above the minimum level. Jump bids, rather than being the norm, were the exception. Throughout stages 1 and 2, activity by most firms was near the minimum necessary to maintain eligibility. These differences are displayed in Figure 3, which shows the revenue and bidding activity by round. Revenue, rather than being a nice concave function exhibiting diminishing changes in revenue with each round, is a series of three hills each defined by the auction stages. The first 30 rounds of stage 2 and the first 16 rounds of stage 3 show no tendency for diminishing changes in revenue. Bidding activity in the narrowband auctions followed a pattern of steady exponential decay as bidders dropped out of the auction or cut back demand. In sharp contrast, broadband bidding activity was a sequence of three bursts in activity at the beginning of a stage followed by decay. The decay in stage 1 was especially dramatic. All major bidders held back, simply bidding to maintain eligibility. By round 10, activity had fallen to a single bid in Detroit.[9]

Activity was restored to above 30% with the movement to stage 2 in round 12. Firms were forced to bid or reduce eligibility. Activity was so steady in the next 18 rounds that in round 31 the FCC raised the bid increment from 5% to 10%. Over the next 20 rounds activity steadily declined until leveling out at about 7% in round 51. A drop in the bid increment in round 60 from 10% to 5% failed to stimulate activity. Hence, in round 65, stage 3 began. Again bidding activity jumped back to over 30%. Steady bidding by AT&T and especially WirelessCo kept revenues increasing throughout the early rounds of stage 3.

---

[9] The auction would not have closed if no new bids were received. The FCC would have moved to stage 2 immediately.

Of the $7 billion raised during the auction, 12.5% was raised in stage 1, 51.8% was raised in stage 2, and 35.6% was raised in stage 3. Despite the importance of stage 3, it is not the case that the earlier rounds served little purpose. Shifts in the allocation of licenses from the end of stage 2 were limited. On licenses covering 76% of the population, the high bidder at the end of stage 2 won a license in the market. Hence, much of the sorting was accomplished in stage 2.

### 5.3 Why so Cautious?

There are several explanations for the absence of aggressive bidding in the broadband auction. First, the lower eligibility ratio and the possibility of tacit collusion suggested to firms that prices might be low in certain markets. The matching might occur at low prices. A cautious, patient bidder might save tens of millions by limiting demands early on. Second, because of the high stakes, broadband bidders were more constrained in their behavior. More elaborate control structures were in place and more individuals were involved in the bidding decisions. The narrowband bidders were relatively small, entrepreneurial companies operating in a highly competitive paging industry. In contrast, the MTA broadband bidders were mostly giant telecommunications companies operating in regulated monopolies or a duopoly cellular industry. One would guess that conservative strategies would be more apt to carry the day in such an environment. Third, the incentives for signaling through large jump bids were much less in the broadband auction. PacTel, for example, would gain nothing by jump bidding in Los Angeles. Everyone knows that PacTel had a strong interest in Los Angeles. A jump bid would add little to this belief. In contrast, the jump bids in the narrowband auctions played a role in sorting out the assignments.

Many auction experts were more surprised by the aggressive narrowband behavior than the conservative broadband behavior. There are good reasons for laying back and letting the other firms push prices up. This is precisely why the auction design includes minimum bid increments and activity rules that assure that the auction will move at an acceptable pace. By hiding in the grass, a bidder lets others reveal information, preserves the possibility of tacit collusion, and reduces the possibility of a bidding frenzy.

### 5.4 Final Results

Table 3 shows the final outcome of the MTA auction. For each market, the table gives the population, the round in which the final bids were placed, the winning firms, the marginal bidder (i.e., the last bidder to drop out), and the bids and the prices ($/pop).[10] Most of the licenses did not receive final bids until late in the auction. Even by the end of stage 2, only 19% of the licenses had final bids.

Prices varied a great deal across markets, but varied little within markets. The similarity of prices within a market is clear. The licenses are near-perfect substitutes and the auction design allows bidders to shift between licenses as prices change. Across markets there is no reason to expect similar prices. Chicago, the most expensive market at $31.90 per pop, and Guam, the cheapest at $0.61 per pop, differ in important ways. Revenues on a per pop basis depend on several factors which vary by market, such as anticipated population growth, income, and cellular use. More importantly, the cost of providing service differs substantially across markets. Buildout costs are much less in densely populated markets that are relatively flat. Chicago is flat and has most of its population concentrated in a small subset of the MTA. Buildout costs are low and the market commands a high price. In contrast, Charlotte ($7.27 per pop) has its population spread throughout a large MTA with hilly terrain. Buildout costs are also low in MTAs like Denver and Salt

---

[10] In the MTA auction, prices are measured in $/pop, rather than $/MHz-pop, since both bands are the same size (30 MHz).

Lake City where most of the population is in relatively flat areas and coverage can be provided from surrounding mountains.

Buildout costs on average are expected to be at least double the license fees (Salant 1995). Hence, any variation in buildout costs will be magnified in the license fee. Suppose a typical market has a license fee of about $15 per pop and a buildout cost of $30 per pop for a total cost of $45. If a particular market's buildout cost is 50% above the norm ($45 not $30), then the market would require a license fee of $0 to maintain the $45 per pop cost. Variation in buildout costs was such that some firms assigned negative values to developing markets with high buildout costs.

Table 4 shows the final outcome by bidder. The bidders are sorted from most to least important in determining prices, where importance is measured by the population coverage of markets in which the bidder either won or was marginal (the last to drop out). 18 of the 30 bidders succeeded in winning licenses. WirelessCo and AT&T were the two most aggressive bidders. Between them they won 58% of the available spectrum. 87.3% of the spectrum was won by the major local and long distance telephone companies. Most of the remainder was won by three other companies: American Portable (a subsidiary of TDS), Western, and Powertel (a large electric utility).

There is a strong correlation between the size of the upfront payment and the amount of spectrum won by a bidder. This association is present in all six auctions. When we regress percent spectrum won with percent upfront payment, we find that the upfront payment is a critical determinant of how much spectrum is ultimately won. The correlation between the upfront payment and the percentage winnings is 78% in the nationwide auction, 83% in the regional auction, 93% in the MTA auction, and 64% in the C-block auction. Some of the correlation in the MTA auction is an artifact of the low total eligibility. Some firms with large upfront payments had to win a large share of the licenses. But the correlation is much stronger than required. A bidder with a large percentage upfront payment tended to win an even larger percent of the spectrum. Bidders with small upfront payments tended to win nothing.

The 30 bidders can be split into three broad categories: national bidders, value-seeking bidders, and regional bidders. Table 5 lists the bidders by type and perceived financial strength. For each bidder, the table gives the bidder's influence on price (measured by the total population coverage of the markets in which the bidder either won or was marginal), and a brief description of the bidder's apparent strategy. Most of the bidders had simple strategies, which I term “sincere.” They bid on a specific set of markets until prices got too high and then reduced demand. Other bidders, such as GTE, adopted a wait and see strategy, avoiding markets of primary interest until later in the auction (Salant 1995). Still others, such as WirelessCo, had complex strategies in which moves into markets were timed to take advantage of the activity rule.

### 5.5 Craig McCaw

A notable absence in the list of winners is Craig McCaw, bidding as Alaacr. Although McCaw did not win any licenses, he played an important role in several key markets. McCaw apparently recognized that in some markets there might not be enough deep-pocketed bidders for prices to reach full value. By putting down just $33 million in earnest money, McCaw gained eligibility to bid in many large markets. At almost no cost (the lost interest on the $33 million upfront payment), McCaw was buying the option to step in and snatch licenses that were underpriced because of a lack of competition. He was an opportunistic bidder, who in the end did not find any opportunities.

To estimate the effect of McCaw's presence, we can look at those markets in which McCaw was the marginal bidder (the last to drop out). One estimate of McCaw's effect on price is the difference between the high bid and the next highest bid without McCaw. In the five markets where McCaw was the marginal bidder, this difference totals $825 million (or $829 when one includes the effect on pioneer revenues). Most of this difference comes from two markets: New York where GTE dropped out at $150 million and Los Angeles where no one else ever bid against PacTel. Due to under bidding, this may overstate McCaw's effect on revenues. For example, even though McCaw was the only bidder to compete with PacTel in Los Angeles, someone else may have stepped in if McCaw was not there. The question is how high another bidder would be willing to go. Los Angeles and New York were too large for the smaller bidders. GTE was the only realistic competitor in these markets. But GTE had little to gain and much to lose by pushing up the prices in Los Angeles and New York.

McCaw's presence was important not only to raise revenue for the government, but also in reducing the possibility of successful tacit collusion. If several markets are going for low prices because of too few deep-pocketed bidders, then the incentive for bidding on other licenses is reduced. A bidder holding an undervalued license is more apt to limit its bidding, because of the possibility that additional bidding will trigger competition for the undervalued license.

Some commentators suggested that Craig McCaw, the largest individual shareholder of AT&T with a 1% stake, was simply bidding with AT&T's interests in mind. McCaw could raise rivals' costs and facilitate tacit collusion by punishing bidders in markets in which AT&T was ineligible to bid. McCaw's behavior appears inconsistent with this hypothesis. McCaw's bidding in under-priced markets tended to upset tacit collusion, contrary to AT&T's interest. Furthermore, by pushing prices higher in the non-AT&T markets, McCaw caused some bidders to switch to AT&T markets, increasing competition and prices in these markets. In all likelihood, AT&T would have been better off with McCaw absent.

Further evidence of McCaw's interest in PCS comes from his subsequent investment in Nextel, which offers an alternative to PCS. It seems that McCaw was looking for the best way to stay in the industry. When exceptional values vanished in PCS, McCaw looked to alternatives. Although Nextel benefitted from higher PCS prices, McCaw did not, since the terms of the Nextel deal were negotiated after McCaw left the auction.

### 5.6 Strategic Bidding

The simultaneous multiple-round auction, by revealing information and giving bidders enormous flexibility in responding to information, tends to minimize the need for elaborate bidding strategies. Nonetheless, a simple strategy of bidding up licenses until price exceeds value is probably far from optimal. Firms bidding in multiple markets have an incentive to under bid; that is, to bid in fewer markets than they desire at current prices (Ausubel and Cramton 1996, Engelbrecht-Wiggans and Kahn 1995). The bidders face a complex matching problem: who should get which licenses? They have a strong interest in resolving this question before prices get too high. The auction can be thought of as a negotiation process in which bidders begin by making conflicting demands. The auction ends when enough bidders reduce demands, so that excess demand is zero. Signaling is a device to facilitate the sorting. Signaling can take the form of public announcements, such as PacTel's repeated announcements that it would win Los Angeles and San Francisco, or it can be through bidding behavior. Code bidding, double bidding, jump bidding, raising one's own bid, and strategic drops or shifts in bids are all examples of strategic bidding.

Code bidding involves using the last few digits of a bid to signal information to a rival. For example, on markets of primary interest, GTE ended its bids with 483, which spells “GTE” on a telephone keypad. American Portable, a subsidiary of TDS, signaled interest in some markets by spelling “TDS” (837) in the last three digits. A more collusive use of a code bid is to tell the bumped rival where to move. A bid of $14,500,039 on Tulsa could tell the bumped bidder to move to market 39 (El Paso). Alternatively, the code bid can threaten the bumped bidder to drop out of the market or face retaliation in another market. If the firm bumped by a bid of $6,200,024 holds a high bid in market 24, the bidder may be telling the bumped firm, "Drop out of this market or expect punishment in market 24." There was some use of code bidding in the MTA auction, but the codes were not as obviously collusive as the last two examples. Some bidding teams decided that such codes were too blatant and ran the risk of antitrust action by the Justice Department.

Double bidding — bidding on both licenses in a market — became a common strategy in stage 3. If the market is contested (there are three or more bidders active in the market) or prices are low, the double bid is a cheap way to maintain eligibility. It also facilitates tacit collusion by maintaining eligibility without moving into a rival's territory. PrimeCo made use of the double bid in the early rounds of stage 3. WirelessCo made extensive use of the double bid, preserving more than 20 million of eligibility through much of stage 3.

The double bidding let WirelessCo store eligibility for later use. This was important because it gave WirelessCo flexibility in deciding when to attack in certain markets. A good example was WirelessCo's behavior toward McCaw. WirelessCo patiently waited for McCaw to use waivers and drop eligibility before bumping McCaw in New York in round 70. In round 74, McCaw dropped out of New York, leaving WirelessCo as high bidder, but bumping WirelessCo in San Francisco in the process. However, McCaw could not return to New York unless it was bumped or withdrew in San Francisco. Hence, WirelessCo left McCaw alone in San Francisco. By round 87, McCaw had used all its waivers and dropped 18 million in eligibility, preventing a return to New York. WirelessCo immediately returned to San Francisco.

Double bidding can help a bidder postpone an attack in particular markets, but it is not without costs. Double bidding exposes the bidder to withdrawal penalties and it may increase prices in the markets with double bids. 8 of the 51 markets closed with a double bidder dropping one of its two bids. Hence, the double bidder often pushed price above what it would have been without the double bid.

Only well into stage 3 did we begin to see jump bidding.[11] WirelessCo placed four jump bids in round 79, double bidding in two uncontested markets (Pittsburgh and Kansas City). It did the same thing in two markets in round 81 (Des Moines and Oklahoma). These jumps were difficult to understand. They did suggest that prices were still low in several markets or else WirelessCo was throwing money away. WirelessCo must have expected further activity in these markets. Indeed, in three of the four markets, there was additional activity. Only in Oklahoma did WirelessCo face a withdrawal penalty as a result of the large double jumps. In two of the markets (Pittsburgh and Des Moines), it paid one bid increment less than the other winner. WirelessCo's double jumps were probably unsuccessful. The message they sent was confusing and led to significant overbidding in Oklahoma.

Although jump bids were rare, there were a few instances where markets closed after a jump bid. For example, PrimeCo's final bid in Chicago was a jump $11.7 million above the minimum bid. WirelessCo dropped out in response. It is impossible to know whether PrimeCo left money on the table or whether the jump induced WirelessCo to drop out.

Strategic shifts or drops can be used to facilitate collusion. In a strategic shift, a bidder shifts to another license to keep prices in other markets from escalating. If firms X and Y are competing in market 1 and firm X is in market 2, then Y switches out of market 1 and into market 2, implicitly telling X to drop 2 to prevent

---

[11] Exceptions were the two jump bids in Los Angeles by McCaw, but these simply pushed the Los Angeles price back in line with other major markets. Southwestern Bell also placed some jump bids in stage 2.

further competition in market 1. In a strategic drop, a bidder drops a license, prompting a reciprocal drop from a competitor. If X and Y are competing in markets 1 and 2, then Y drops market 1, implicitly telling X to drop market 2. Strategic shifts and drops have two difficulties, which limit their use. First, the implicit message is much less clear than with a gift withdrawal or code bidding. Second, strategic shifts and drops are only effective once the competition is down to two bidders. Prices at this point may already be high. There is little evidence that strategic shifts or drops were used successfully to limit competition.

In special circumstances, raising one's own bid may be a good strategy. If the high bidder believes that the remaining competitor would be willing to bid up one bid increment, but not two, then the high bidder may benefit from raising its own bid. PrimeCo successfully anticipated GTE's final bid in Jacksonville. PrimeCo raised its own bid in round 108, topping GTE's final bid in the same round. A good example of the cost of such a strategy is Powertel's $2.5 million raise of its own bid in Jacksonville in round 110. Powertel expected GTE to come back in Jacksonville, but GTE had decided to drop the market. Another costly example is WirelessCo's experience in San Francisco. In round 97, WirelessCo, Alaacr, and American Portable were still competing for the remaining San Francisco license (it was assumed that PacTel would win the other). WirelessCo was the high bidder and had just made the gift withdrawals of Tampa and Houston to get American Portable to move off San Francisco. WirelessCo expected Alaacr and perhaps American Portable to come back in San Francisco. In anticipation of this competition, WirelessCo raised its own bid by $14.4 million. But the competition did not materialize. Both Alaacr and American Portable dropped out of San Francisco.

For the most part, bidders tended to bid on the cheaper of the two bands. However, in several cases this rule was not followed. There are two reasons for bidding on the more expensive license. First, the bidder may prefer one band over the other, because it expects to win neighboring licenses of the same band. AT&T attempted to get band A in most of its markets; PrimeCo favored band B. Second, it may make sense to bid against the weaker bidder to avoid punishment in other markets. A bid against the strong firm may upset tacit collusion and drive prices higher. In four markets, the final bid was on the more expensive license against a smaller (weaker) bidder. AT&T bumped PCS America in Buffalo rather than the slightly cheaper license held by WirelessCo. In Detroit, WirelessCo bumped American Portable, rather than AT&T although it was $1 million more. In Atlanta, AT&T bumped Powertel, not GTE although it was $4.3 million more. In Minneapolis, WirelessCo bumped Continental although it was $1.3 million more than American Portable. One possible explanation for this behavior is that the bidder was concerned with retaliation in other markets. Otherwise, bidding against the strong bidder is the better strategy. It saves money and raises the cost of a strong competitor.

Strategic bidding played a more important role in the MTA auction than in the narrowband auctions, because of the reduced competition. However, even in this auction, much of the strategic bidding did not seem to improve the bidder's position. Subtle signaling was especially ineffective.

### 5.7 Bid Withdrawals

Bid withdrawals are another example of strategic bidding. The purpose of allowing withdrawals is to let bidders back out of failed aggregations. There were 21 withdrawals in the auction. All but two were in stage 3. However, none of the withdrawals seems to be motivated by an exit from a failed aggregation. Rather the withdrawals appeared to be for some other strategic purpose.

There are several reasons for withdrawing a bid:

- To back out of a failed aggregation. The withdrawal follows being bumped on complementary licenses. The bidder either drops eligibility or shifts to another set of complementary licenses.

- To increase flexibility in the next round of bidding. A bidder with little free eligibility might want to shift among licenses in the next round.
- To maintain eligibility or raise rivals' costs. A bidder might engage in a fight for a license it is not truly interested in. It then withdraws when the competitor drops out.
- To maintain eligibility without raising prices. A bidder withdraws from a license and then places a minimum bid. When repeated, this maintains eligibility, but prices do not rise, so long as a competitor places the minimum bid. The withdrawal signals to others that the bidder is not truly interested in the license.
- To make room for another bidder to drop down. In a fight with another bidder, a bidder might withdraw to suggest that the competitor move to the withdrawn license rather than continue the fight. This facilitates tacit collusion by offering a gift and then lowering the cost of punishment. It is easier to punish bad behavior by the bidder that takes over a withdrawn license. A raise by the bidder that withdrew is essentially costless, since the withdrawn bid amount is already committed.

Table 6 shows the 21 bid withdrawals in the auction. WirelessCo made 11 of the 21 withdrawals. Only 6 withdrawals resulted in penalties. The $14.836 million in penalties were paid by WirelessCo ($14.514 million) and American Portable ($0.322 million). Most of the withdrawals were to maintain eligibility (11 of 21) or increase flexibility (5 of 21). WirelessCo's extensive double bidding resulted in only two withdrawals (Minneapolis and Oklahoma) with penalties of $3.851 million. None of the withdrawals appeared to be caused by predatory bidding (bidding up a license to raise a rival's costs).

One pair of withdrawals was apparently intended as a gift to entice a competitor to shift to the withdrawn licenses. In round 97, WirelessCo withdrew from Tampa and Houston, hoping that American Portable would take this gift and move off San Francisco. American Portable accepted the gift, moving down to Tampa and Houston in the next round. WirelessCo's gift cost it $8.505 million in penalties, but this is less than one bid increment in San Francisco.

A possible implication of the withdrawals in stage 3 is that some licenses might go unsold. Late in stage 3, bidders might not have the eligibility to pick up withdrawn licenses. Fortunately this did not happen. Most of the withdrawals near the end of the auction were to increase flexibility in the next round. If the licenses were not picked up by a competitor, then the withdrawing bidder picked up its own withdrawals.

## 6 The C-Block Auction

The next auction was for the third (and final) 30 MHz block of broadband spectrum, the C-block. 493 BTA licenses were sold to small businesses (annual revenues less than $40 million). Large firms were not eligible to bid. Although this auction was to start shortly after the MTA auction finished, the auction was delayed for 6 months in the courts.[12] The C-block auction finally began on December 18, 1995, and

---

[12] On March 15, 1995, the U.S. Court of Appeals in the District of Columbia stayed the auction until the court could hear the case brought by Telephone Electronics Corporation (TEC), a rural telephone company. TEC claimed that it was unfairly excluded from the auction and questioned the constitutionality of bidder preferences for women and minorities. In early April, TEC withdrew its lawsuit in a settlement with a third-party. PCS PrimeCo, a major bidder in the MTA auction, agreed to give TEC what it wanted. The auction, which was scheduled to begin in June 1995, was postponed until early August. The auction was postponed again when the June 12 Supreme Court decision in *Adarand v. Pena* made it likely that the race and sex

concluded nearly 5 months later on May 6, 1996, after 184 rounds. Revenues net of the 25% bidding credit were $10.2 billion, more than double the prices in the MTA auction.

Figure 4 displays the bidding activity and revenue by round. Bidding activity was much higher than in the MTA auction — so much so that the stage transitions were hardly noticeable. Bidders did not hold back as they did in the MTA auction. Prices quickly escalated to well beyond MTA prices. Early activity was especially strong in the major markets. This is consistent with the major markets (e.g., Chicago) being key to a synergistic combination in a broader area (the midwest). Bidders wanted to resolve the major markets before going after the smaller complementary markets. Bidding in the second half of the auction was almost exclusively on these smaller markets.

Many were shocked by the high prices. What accounted for average net prices of $39.88 per pop in the C-block, compared with $15.54 per pop in the MTA auction? There are two main explanations: installment payments and competition.

The small bidders in the C-block auction were given attractive payment terms to compensate for difficulties in raising capital. C-block winners pay 5% at the end of the auction, 5% at the time of award, and then ten years of installment payments at the 10-year Treasury note rate. The quarterly installments cover interest only for the first six years. During the auction the 10-year T-note rate was about 6.5%. If we assume a cost of capital for the firm of 14%, then this 7.5% spread amounts to an additional bidding credit of 32%. With a 16.5% cost of capital (10% spread), the installment payments give an additional bidding credit of 40%. Hence, the C-block price of $39.88 becomes .6·39.88 = $23.93.

This calculation ignores the option value created by the back-loaded installment plan. To the extent that there is uncertainty about the value of spectrum, the option of default in case spectrum has a low value makes a license worth more than its expected value. Nonetheless, an effective bidding credit from installments in the range of 30 to 50 percent seems about right. At 40%, the installment payments account for about $16 of the $24 spread between the C and A-B prices.

The second important factor explaining the higher prices was the much greater competition in the C-block. Competition in the MTA auction was weak in several of the major markets. In contrast, competition in the C-block auction was strong in all markets. The eligibility ratio (total eligibility in pops divided by total pops being auctioned) was 6.75, compared with 1.93 in the MTA auction. There were 255 bidders compared to 30 in the MTA. 89 bidders won licenses, rather than 18 in the MTA.

Ausubel and Cramton (1996) demonstrate that larger bidders have a greater incentive to reduce demand in order to keep prices low. Hence, having a large number of small bidders is more competitive than a small number of large bidders, holding the eligibility ratio fixed. Moreover, competition may have been heightened by the fact that in many cases the bidders were startups that would be out of a job if licenses were not won.

---

preferences would not survive a constitutional challenge. The FCC modified the rules to give all small businesses, regardless of race or sex, the same 25% price preference and attractive payment terms. Previously, only women or minority controlled firms were eligible for the most attractive terms. The auction was rescheduled to August 29. The C-block auction was stayed a third time on October 18, in response to Radiofone's challenge of the PCS/cellular cross-ownership rule, which limits the amount of broadband PCS spectrum that a cellular licensee can acquire in its cellular market. On October 25, Justice Stevens, Circuit Justice for the Sixth Circuit, vacated the stay. On October 30, the full U.S. Supreme Court declined to overturn Justice Stevens' Order dissolving the Sixth Circuit stay.

The importance of competition in determining prices is seen by comparing prices in the four largest MTAs (Table 7). The C-block prices have been discounted by 40% to account for the installment payments. Notice that the C-block prices are fairly close. In contrast, the Chicago MTA price is well above the other MTA prices. In Chicago, all three nationwide bidders (WirelessCo, AT&T, and PrimeCo) were eligible to bid; whereas, in New York and San Francisco, only WirelessCo was eligible. This lack of competition in New York and San Francisco seems the only compelling explanation for the low prices in these markets, relative to Chicago. Judging from these markets, the discounted C-block prices are not out of line with the prices on the more competitive markets in the MTA auction. This conclusion is supported by the price regression in Ausubel, et al (1996). The strongest determinant of prices in the MTA auction was the level of competition, measured as the eligibility in the market over the total eligibility. In the C-block auction this variable was insignificant, since all markets were competitive.

**Table 7.** Price Comparison in Major Markets ($ per person in 1994)

| Market | C-block price with 40% installment discount | MTA price |
|---|---|---|
| New York | 27.74 | 16.52 |
| Los Angeles | 26.47 | 24.05 |
| Chicago | 27.18 | 30.40 |
| San Francisco | 31.54 | 16.10 |

The high C-block prices raised the concern that some winners may default. Indeed, the fourth largest winner (BDPCS) failed to make the initial 5% down payment, defaulting on 17 licenses for which it bid $874 million. BDPCS was expecting the down payment to come from US West, but apparently US West changed its mind about funding BDPCS. The FCC quickly decided to reauction the licenses. The reauction began on July 3 and ended on July 16 after 25 rounds. By the fifth day of bidding (round 16), net revenues of the reauctioned C-block licenses already matched the $874 million total from the default. On day six, the auction was nearly over with two consecutive rounds with no new bids (the auction remained open, because at least one firm submitted a proactive waiver). Final net revenue was $905 million, 3% greater than in the initial auction. In all but four markets, the reauctioned licenses sold for within 25% of the original prices.

Aside from this default, which was quickly corrected, the auction was successful. There surely will be future defaults, given the large number of small businesses that won licenses. However, this must be expected in an auction involving such substantial sums and yet small upfront payments.

This auction demonstrated the feasibility of conducting simultaneous multiple-round auctions with hundreds of licenses and hundreds of bidders. Although the auction was long, the long duration gave bidders and capital markets time to make difficult decisions that determined the assignment. The speed of the reauction indicates the importance of price uncertainty in determining auction duration.

## 7 Auctioning Encumbered Licenses

Two other auctions were conducted at the same time as the C-block auction. The MDS (wireless cable) auction had the same structure as the C-block: a single license in each of 493 BTAs. In the SMR auction, 20 licenses were sold in each of 51 MTAs (1020 licenses in total). Both of these auctions involved the sale of heavily encumbered licenses. The FCC had previously awarded numerous MDS and SMR licenses of limited geographic scope. In these auctions, winners must protect incumbents against interference. Hence, what was sold was like swiss cheese with large holes in some of the most desirable areas. As a result, MTA and BTA populations were no longer a relevant measure of the size of a license. Instead, the FCC used "bidding units," which were an attempt to measure the size of the effective population covered by a license.

Both auctions attracted a large number of bidders (155 for MDS and 128 for SMR), but the initial eligibility ratios (3.6 for MDS and 2.4 for SMR) were well below that of the C-block. Figures 5 and 6 show the bidding activity and revenue by round. The stage transitions are noticeable in both, suggesting a mild tendency for the bidders to hold back. However, neither had the large swings in activity found in the MTA auction.

The discontinuous jump in revenues in round 9 of the SMR auction was the result of a mistaken bid. Atlanta Trunking intended to bid $125,025, but added three extra zeros, and submitted the bid of $125,025,000. Atlanta Trunking immediately withdrew the bid, but according to the FCC rules was liable for a withdrawal penalty well in excess of $100 million. This was the first mistaken bid in FCC spectrum auctions, but not the last. Three mistaken bids were placed in the C-block auction. MAP added an extra zero to its bid in round 10. Then only two rounds later, PCS 2000 made the same mistake on a larger license. Finally, in round 38, Georgia Independent added an extra zero as well. Given that over 60,000 bids were placed in these three auctions, it is not surprising that a few mistakes were made. The FCC responded to these mistaken bids by modifying the software to warn the bidder if a bid appears to be a mistake. In addition, they adopted a rule for mistaken bids. The rule limits the size of the penalty in the event of a mistaken bid, but still imposes a penalty sufficient to discourage mistakes.

In the SMR auction, the incumbents expressed concern that they might be at a disadvantage in the auction. They argued that they were vulnerable to speculators, to predatory bidding, and would have less flexibility in stage 3 to move to unencumbered licenses. I was of the opinion that incumbents were at an advantage. The incumbent would be buying areas that complement its existing licenses; whereas, the nonincumbent would be buying swiss cheese with substantial interference problems. As it turned out, incumbents paid significantly less than nonincumbents.

## 8 Assessing the Auction Design

Since we do not observe the values firms place on licenses, it is impossible to directly assess the efficiency of these auctions. Nonetheless, we can indirectly evaluate the auction design from the observed behavior. To aid in comparing and assessing the auctions, Table 8 presents summary statistics for each auction. These statistics are discussed throughout this section.

### 8.1 Extensive Information was Revealed by the Bidding

Two essential features of the design are (1) the use of multiple rounds, rather than a single sealed bid, and (2) simultaneous, rather than sequential sales. The goal of both of these features is to reveal information and then give the bidders the flexibility to respond to the information. This should reduce the winner's curse and more importantly facilitate efficient aggregations. Proponents of sequential auctions have argued that the information revealed in a simultaneous auction is of little help to the bidders, because it is only preliminary information. The final outcome may be far from the current state, even near the auction's end. Using the data from the auctions, I evaluate both the quality of the information revealed in the auction and the ability of firms to respond to the information. There are two dimensions to the information: the assignment of licenses and the prices of the licenses. Each is considered in turn.

As observed earlier, the upfront payment is an excellent indicator of the quantity of spectrum won. It, however, tells us nothing about which licenses a firm will win. For this bidders must look at the bids during the auction. In each of the auctions, much about the final assignment was determined well before the auction's end.

In the nationwide auction, the high bidders in round 28 were the same as in the final assignment 19 rounds later, except for one license. Only a few questions remained, such as which firms would get the two 50s. Well before round 28, it was clear who was likely to win the 50/50s and 50/12s. The assignment in the regional auction settled even more quickly. By round 10, the high bidders were the same as in the final assignment 95 rounds later.

One might expect that the MTA auction would present a different picture, because of the rampant under bidding in stages 1 and 2 of the auction. However, despite this under bidding, the current assignment revealed a great deal of information about the final assignment. Figure 7 tracks by round the fraction of current high bidders (pop weighted) that eventually win in their current markets. This fraction, which hits 50% in the second round, gradually increases throughout the auction. At the end of stage 2 (round 64), 76% of the current high bidders were still high at the end of the auction (round 112). The major exceptions were in New York, Chicago, and Washington.

The clarity of the assignments stems from the fact that most bidders had focused interests. They bid on a relatively small set of licenses throughout the auction, although they were typically eligible to bid on much more. As a result, the number of active bidders in each market was small. Table 9 shows the distribution of the number of excess bidders in each market. It is based on the number of bidders that were active in the market after stage 2. A typical market had 3 excess bidders (5 bidders in total) over the entire auction. By the end of stage 2, there was only a single excess bidder in a typical market.

**Table 9**. Distribution of Excess Bidders in Markets (Population Weighted)

| Number of excess bidders in market | 0 | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|
| Percent of markets over entire auction | 0 | 13 | 20 | 41 | 20 | 6 |
| Percent of markets after stage 2 | 15 | 42 | 30 | 11 | 1 | 0 |

The current bids provide good information about final assignments, but what about prices? Again, in all six auctions, current prices give good information about relative prices at end of auction. Figure 8 displays the correlation between current and final prices throughout the MTA auction. Initial bids are only modestly correlated with final prices (30%). This correlation does not increase until stage 2, but then increases sharply in the early rounds of stage 2, reaching 62% by round 21. From round 21, the correlation increases steadily throughout the remainder of the auction. The correlation is 83% at the end of stage 2.

The remaining question is whether bidders have the flexibility to act on the information. By the time firms have a good sense about prices and the assignment, they may not have sufficient eligibility to respond. Clearly this was not the case in the narrowband auctions. In the nationwide auction, firms maintained their full eligibility throughout the auction, since the auction never moved out of stage 1. In the regional auction, the assignment and prices settled early. Bidders had good information about the outcome throughout stage 2 and had plenty of flexibility to shift among licenses.

The biggest concern about flexibility came in the MTA auction, where much of the action did not occur until stage 3. Figure 9 shows the eligibility ratio by round. Starting at 1.93, the eligibility ratio fell to 1.53 by the end of stage 2. Hence, at the end of stage 2, there is good information about prices (83% correlation with final prices) and assignments (76% eventually win), and yet plenty of eligibility (1.53) to shift among licenses in response to this information. This flexibility was observed in the firms' behavior through most of stage 3. Firms bidding on several licenses were able to move among different sets of licenses, only losing an insignificant amount of eligibility. American Portable and others made such shifts in several rounds. The fact that there was much movement among licenses as prices changed suggests that the simultaneous design was important in determining the outcome.

The extensive information about prices and assignments is not simply a result of markets closing early. Figure 10 shows the fraction of licenses by round with final bids (pop weighted). At the end of stage 2 only 19% of the licenses had received final bids. By round 74, the correlation between current and final prices was up to 89%, even though final bids had been received on only 25% of the licenses. A great deal of bidding was still to take place, but the information about the eventual outcome was excellent.

### 8.2 Similar Items Sold for Similar Prices

An advantage of the simultaneous ascending-bid design is that it tends to generate market prices. Similar items should sell for similar prices. There is strong evidence of this in all six auctions. In the nationwide auction, the price differences among similar licenses were at most a few percent and often zero. In the regional auction, price differences were larger, but still small with the exception of one license with a bid withdrawal late in stage 3. The importance of forming nationwide aggregations within the same band was probably the source of the larger differences in prices. In the MTA auction, only the A and B licenses within the same market are directly comparable. A and B prices differed by less than one bid increment in 42 of the 48 markets. In the six markets where prices differed by more than an increment, three involved withdrawals (two to maintain eligibility and one gift) and three were to avoid strong bidders, which was especially important if the strong bidder favors one band.

The generation of market prices is important from an efficiency viewpoint. In addition, it contributes to a sense among the bidders (and observers) that the auction is fair. Most bidders in all six auctions walked away feeling satisfied by the process, even if they were disappointed by the outcome.

The simultaneous stopping rule is an important factor in achieving market prices and efficiency. Market-by-market closing would not give the bidders sufficient flexibility. With market-by-market closing, the auction is essentially a sequential auction with endogenous order. A license may close by the time a bidder wants to shift to it. This possibility was seen in each of the auctions. It was common for licenses to have no bids for several rounds followed by steep increases in price. For example, in the nationwide auction, bids on the 50/50s stopped for seven rounds (from round 20 to 26) at $70 million, but then increased to $80 million. Prices on the 50/12s had to increase before bidding could continue on the 50/50s. This tendency for long pauses in activity in particular markets was even more pronounced in the MTA auction.

### 8.3 Efficient Aggregations were Formed

Valuations depend on the set of licenses won. Hence, it is important to use an auction form that allows bidders to express these value interdependencies. Such a design would encourage the formation of efficient aggregations. Supporters of the simultaneous ascending-bid design argued that bidders would have sufficient flexibility to express valuations for combinations of licenses, even without package bids.

However, others argued that package bids would be essential to achieving efficiency. They feared the exposure problem would discourage bidders from going after synergistic gains. Evidence from the auctions suggests that bidders were able to form efficient aggregations without package bids.

In the nationwide auction, the aggregation problem was simple. Bidders acquiring multiple bands preferred adjacent bands. In all cases, bidders acquiring multiple bands were successful in winning adjacent bands (PageNet won bands 1 and 2, and McCaw won bands 3 and 4).

In the regional auction, the aggregation problem was more complicated. Several bidders had nationwide interests. These bidders would have to aggregate all five regions, preferably all in the same band. The bidders were remarkably successful in achieving these aggregations. Four of the six bands sold as nationwide aggregations. Bidders were able to win all five regions within the same band. Even in the two bands that were not sold as nationwide aggregations, bidders winning multiple licenses won geographically adjacent licenses within the same band. The regional auction demonstrated that in this setting it is possible to build large aggregations without allowing package bids.

Large aggregations also were formed in the MTA auction. Overall, there was a tendency for bidders to win the same band when acquiring adjacent licenses. AT&T was high bidder on the A band in its top markets and PrimeCo was the high bidder on the B band in its top markets. The large aggregations won by WirelessCo, AT&T, and PrimeCo appear to have efficient geographic coverage when one includes cellular holdings. WirelessCo won nationwide coverage except for a single strip of licenses from Cleveland to Tampa and a few other holes (most notably Chicago). PrimeCo won nationwide coverage except for a single block of licenses in the central U.S. Likewise, AT&T was able to fill its cellular holes except for three regions. The absence of package bids did not seem to prevent firms from forming efficient aggregations. However, it is certainly possible that efficiency was reduced, because of under bidding. High-value bidders may have dropped out of markets too soon to keep prices on other markets from escalating.

Further evidence of efficient aggregations comes from the absence of bid withdrawals. There were no withdrawals in the nationwide auction. The two withdrawals in the regional auction were minor. They were caused by strategic bidding unrelated to a bidder backing out of a failed aggregation.

Withdrawals in the MTA auction did not suggest aggregation failures. The withdrawals through stage 2 were of no importance. There was an increase in withdrawals in stage 3, but they were mostly motivated from efforts to maintain eligibility, rather than by aggregation failures. A few were attempts to end competition in other markets. If successful, such attempts might reduce efficiency, but they only succeeded in one case. No withdrawals were to back out of failed aggregations. Exposure, then, did not seem to be a problem preventing efficient aggregations.

The C-block auction had 50 withdrawals out of nearly 30,000 bids. Most of these occurred early in the auction. Intouch, for example, made 12 withdrawals in the first 10 rounds, apparently for some signaling purpose. There were no withdrawals in the last 55 rounds of bidding.

Certainly there are settings in which the exposure problem is severe and efficiency is destroyed by not allowing package bids. Experimental evidence is given in Bykowsky, et al. (1995). These tend to be settings with extreme synergies, where a missing piece makes the collection worthless. Real estate projects and room on the space shuttle have this character. However, the synergies in PCS licenses are much less severe. MTA licenses are sufficiently large to capture much of the regional synergies. There is some benefit to having adjacent licenses and there may be other marketing or network synergies, but they are not 0-1. Those favoring package bids may have overestimated the extent of the exposure problem.

Ausubel, et al. (1996) analyze the MTA auction data to see if there is evidence that synergies caused bidders to pay more for adjacent licenses. They find no such evidence, which suggests that the exposure problem probably did not hamper the formation of efficient aggregations.

### 8.4 Tacit Collusion was Limited

The simultaneous multiple-round auction gives bidders a great deal of information and provides enormous flexibility in responding to this information. In a competitive auction, this information and flexibility should improve efficiency, but it also opens to the door to more collusive strategies. Is there any evidence of collusion in the early PCS auctions? There are two main concerns: limiting competition through alliances, followed by tacit collusion during the auction.

There was no evidence of collusion in either the nationwide or regional auctions. Alliances were unimportant in the nationwide auction. The successful firms bid on their own. In the regional auction, alliances were formed between designated entities and established paging companies. The alliances transformed weak bidders into strong companies capable of competing with the industry leaders. Bidding was aggressive and competitive throughout both narrowband auctions. Marginal bidders dropped out only after long fights with the eventual winners. Jump bidding, although pervasive, seemed ineffective at steering competitors to other licenses. Prices were higher than many predicted. Even when excess demand was small, bidders were unwilling to scale-back demands in order to close the auction at substantially lower prices.

Collusion was much more of an issue in the MTA auction. The PrimeCo alliance presented the biggest problem. It transformed four deep-pocketed bidders with extensive market eligibility into one deep-pocketed bidder with limited market eligibility. It created the possibility of slight competition in some major markets, such as New York and Los Angeles, and reduced competition in other markets. In contrast, the WirelessCo alliance probably increased competition by creating a strong nationwide bidder from companies that would have been much weaker on their own.

The PrimeCo alliance greatly increased the chances of successful tacit collusion. This is the primary explanation for the rampant under bidding in the early stages of the MTA auction. Given the possibility that the matching could occur at low prices, there was no incentive for firms to bid aggressively. The low activity requirement in stages 1 and 2 meant that bidders could bid well under their true demands and yet preserve most or all of their eligibility. As such, firms tended to limit their bids to what they wanted most.

Fortunately, tacit collusion is easily upset. It requires that all the bidders reach an implicit agreement about who should get what. With thirty diverse bidders unable to communicate about strategy except through their bids, forming such a unanimous agreement is difficult at best. Although some bidders had clear interests in a few licenses, other bidders like Alaacr and American Portable simply were looking for value. These value-seeking bidders can have large demands at low prices and are hard to punish. In addition, the nationwide goals of WirelessCo, AT&T, and PrimeCo were incompatible. Not all three could succeed in forming a nationwide aggregation. How much should each cut back to allow room for the other two, as well as the smaller bidders? Disagreements were bound to arise and these disagreements would limit tacit collusion.

Fears of collusion peaked in round 10 of stage 1 when bidding activity plunged to just a single bid in Detroit despite bargain prices. But with the onset of stage 2, bidding activity jumped back up and remained strong. Bidders refused to cut eligibility until well into stage 2. Sorting out who should get what was not going to be accomplished without the price mechanism. Nonetheless, it was clear that stage 3 would be needed to push prices up. By round 60, activity had once again dropped below 10%. Many bidders could maintain eligibility in stage 2 by simply sitting on their high bids.

Strong bidding early in stage 3, especially by WirelessCo and AT&T, put fears of tacit collusion to rest. These firms needed to cut eligibility significantly for the auction to close and neither expressed any interest in doing so. The auction did not end until the average price surpassed government estimates. In a 1992 study, the Congressional Budget Office estimated prices to be between $3.50 and $15.00 per pop. In 1994, the Office of Management and Budget estimated a price of $12.47 per pop compared with the actual average price of $15.54 per pop. Estimates based on recent cellular transactions would be much higher, but it is difficult to unbundle the license value from the value of the network and existing customers.

Narrowband prices ($3.10 per MHz-pop in the nationwide auction and $3.46 in the regional auction) were about six times higher than broadband prices ($.52 per MHz-pop). However, this is not evidence of collusion in the MTA auction. The narrowband and broadband prices are not comparable, since it would be difficult to use broadband spectrum for narrowband applications. The imbalance simply reflects the different supply and demand conditions in the two markets. It does suggest that the FCC should go ahead with its plans to allocate more narrowband spectrum.

Although tacit collusion failed overall, there may have been some markets where bidders dropped out early to improve the outcome in other markets. For example, American Portable decided to drop out of San Francisco in response to WirelessCo's withdrawal in Tampa and Houston. However, WirelessCo raised its own bid in San Francisco in the round that American Portable dropped down to Tampa and Houston, so this “tacit collusion” was far from perfect. In addition, WirelessCo rebid in Houston later in the auction, bumping American Portable. After a careful review of the bidding, I was unable to find any clear cases of successful tacit collusion.

In those markets that appear to be especially good values (New York, Los Angeles, and San Francisco come to mind), the critical feature seems to be an absence of deep-pocketed bidders. My assessment is that the PrimeCo alliance had more to do with these good values than the success of tacit collusion.

The auction outcome might have been radically different without the value-seeking bidders, especially Craig McCaw and American Portable. There was close to too little competition in the MTA auction. It is in precisely such circumstances that the simultaneous multiple-round auction is most vulnerable to collusion. In future auctions, it may make sense to reduce collusion risk by limiting alliances among major players in the industry. Such restrictions are common. For example, the top oil companies are not allowed to partner in oil lease auctions. However, it is not at all clear what rule the FCC could have adopted to prevent the PrimeCo alliance and yet encourage synergistic alliances. Formulating general rules would be complex if not impossible. Preventing such alliances on a case-by-case basis would likely delay the auctions and lead to litigation.

### 8.5 The Auction Durations were Reasonable

An important advantage of auctions is their ability to quickly assign licenses to high value uses. The sooner licenses are assigned, the sooner companies can provide services demanded by consumers. Hence, in judging the auction design, we must consider how long it takes to conduct the auction.

Certainly the narrowband auctions were concluded in a timely manner. The nationwide auction took one week and the regional auction concluded in two weeks. Other auction designs could assign the licenses more quickly, but given the importance of the licenses to the firms involved, a more hasty process would be foolish. Companies needed time to think through their options. The short auction durations were possible in these auctions, because of the small number of licenses up for auction (10 in the nationwide and 30 in the regional) and the relatively low stakes. This meant that many rounds could be conducted in a day. Toward the end of the auctions, when bidding activity was low and few decisions were being made, more than one round occurred each hour.

The MTA broadband auction concluded after about three months. This may seem like a long time, but given the magnitude of the decisions involved three months is a modest duration. The speed of the auction was limited by the large number of licenses (99) and the very high stakes. The auction can only go as fast as the bidder that needs the most time. WirelessCo's bidding was especially complex, because of the large number of licenses it was interested in. WirelessCo urged the FCC not to do more than two rounds per day. It was hard not to listen to WirelessCo's plea, since it was the largest bidder and had a legitimate concern.

Probably the largest cost of the three month duration is in postponing subsequent auctions. The remaining broadband auctions cannot begin until after the MTA auction. Companies need to know the MTA outcome before forming alliances and attracting investors. However, the cost associated with a three month delay is probably minimal. Companies also need time to develop plans and get capital in line.

The final three auctions, with many more bidders and licenses, took about four months, 180 rounds, and 80 days to complete. All three auctions had long final tails that involved few bids and little change in revenue or assignment. The FCC did well to shorten this tail by conducting many rounds per day. By the end, 8 or more rounds per day were held in each auction.

Certainly compared with prior methods of assignment the auctions have been successful. Even with streamlined comparative hearings, it took the FCC an average of two years to award thirty “non-wireline” cellular licenses (licenses not limited to local telephone companies). After the FCC switched to lotteries in cellular service, the average time to award a non-wireline license decreased to about one year. With auctions, the average time to award licenses has been less than a year. Of the ten nationwide narrowband PCS licenses, seven were awarded in under two months and the remaining three in under five months. The thirty regional narrowband PCS licenses were awarded in approximately three months. The 99 MTA broadband PCS licenses took three months and the licenses were awarded in four months from the close of the auction. It should be noted that the length of an auction depends in part on policy decisions and that faster is not always better. In the case of the MTA broadband auction, most of the auction was conducted with two rounds per day so that bidders would have sufficient time to evaluate the results of the previous round and plan their bidding strategy.

### 8.6 Minimum Bid Increments were Needed

Minimum bid increments play an important role in controlling the pace of the auction. If set too high, the increments choke off bidding, even when the high bidder does not have the highest value. If set too low, the auction may last too many rounds if bidders bid at the minimum level. Large increments are especially useful early in the auction when activity is high and prices are low. There is little cost to large increments early in the auction. Large increments are inefficient only when they prevent the highest valuer from placing a bid. But if prices are low, the highest valuer can easily top the high bid by the minimum increment. Inefficiencies only appear when a license is about to close and the size of the inefficiency is at most one bid increment. (Markets do not literally close license-by-license. Individual licenses “close” in the sense that there are no further bids in the market.) Thus, the auctioneer can start with a large increment and then reduce the increment as the probability of closure increases. In the nationwide auction, where all of the licenses were good substitutes, overall bid activity was an excellent measure of when licenses were about to close, so a sensible rule tied the bid increment to bid activity.

In the MTA auction, licenses in different markets are not good substitutes and there is much greater variation in prices across markets. The FCC had no way to know when markets were likely to close. Also with so many licenses, it made sense to have a single rule for setting increments across all licenses. In the standard rule, the minimum increment is the greater of a percentage increment or a per-pop increment. Initially, the percentage increment was 5% and the per-pop increment was \$.60 per pop (or \$.02 per MHz-pop). In this case, until the price reaches \$12 per pop, the per-pop increment would bind. Before a license receives a bid, the minimum increment is 0. This prevents licenses worth less than \$.60 per pop from going unsold.

Early in stage 2, bidders continued to bid at the minimum level, but eligibility did not drop. Hence, to speed the auction along, the percentage increment was doubled to 10% in round 31. By round 31, the 10% increment was greater than the per pop increment in many important markets. The fact that the percentage increment was 5% at the beginning of the auction was largely irrelevant, since early in the auction it is the per pop increment that is binding. The per-pop increment remained \$.60 per pop. The rationale for leaving the per-pop increment fixed was that several of the low-priced licenses might be near closure and this would reduce any inefficiencies on these licenses.

At the end of stage 2, the percentage increment had been cut back to 5%. When stage 3 began with the same strong activity seen in the beginning of stage 2, the FCC considered whether to raise the percentage increment to 10% again. This option was rejected and with good reason. In stage 3, activity drops as bidders reduce eligibility by permanently dropping out of markets. It is precisely at this point — the point when reservation prices are reached — that a modest bid increment is desired. Markets closed throughout the remainder of stage 3. This is seen in Figure 10, which shows the fraction of licenses (pop weighted) with final bids by round. Licenses did not begin to close until midway through stage 2 (about round 36). By the end of stage 2 (round 64) only 19% of the licenses had received their final bids. The remaining 81% of the licenses closed throughout stage 3 at a rapid and steady pace. Hence it was important to keep the bid increment low throughout stage 3.

Based on similar reasoning, there is little point in dropping the bid increment late in stage 3. Toward the end of the auction, the vast majority of markets have already effectively closed and there is no way for a bidder to return to a market to take advantage of a lower increment. The lower increment then is only effective in the few markets that have yet to close. Since there is no way to predict when reservation prices may be reached in these markets, dropping the increment to 2% might greatly extend the auction (as was the case in the regional auction). The efficiency and revenue gain is likely small, since the low increment only applies to the few markets that have yet to close. Hence, it made sense to keep the increment at 5% throughout stage 3.

In retrospect, the MTA auction could have been sped up without much efficiency loss by adopting larger bid increments in the early rounds. Increments of 10% or \$1.20 per pop in the first thirty rounds would have shortened the auction by more than a week. These adjustments were made for the final three auctions.

In future auctions, the FCC plans to further quicken the pace by using even larger bid increments early on. A difficulty with large increments is that some licenses may be close to final prices when others are far from final prices. To avoid this problem, the FCC plans to use license specific increments, where activity is used as an indicator that the license is far from the final price and a larger increment is in order. In the C-block it was not uncommon for some licenses to have no new bids and for others to have a dozen.

### 8.7 The Activity Rule Worked Well

One potential problem with the MTA broadband auction was the fact that prices and assignments shifted substantially in stage 3. Ideally, most of the action would take place in stage 1 and stage 2, when the less restrictive activity requirements were in place. Bidders in the early stages have great flexibility in shifting among licenses. In stage 3, flexibility is curtailed, increasing the possibility of inefficient assignments.

Perhaps surprisingly, the stringent stage 3 activity requirement did not pose a major obstacle to large bidders. Bidders were able to maintain eligibility through double bidding. Even without the double bid, firms bidding on several licenses were able to move among different sets of licenses, only losing an insignificant amount of eligibility. However, stage 3 does distort behavior. In each round, firms placed strategic bids to maintain eligibility and withdrawals were more common. Nonetheless, it does not appear that this strategic bidding severely reduced efficiency.

In stage 3, it is possible for the auction to effectively become a sequence of auctions from largest market to smallest as bidders drop down to smaller licenses. Bidders may not have the flexibility to make more sophisticated shifts. This hypothesis can be tested by looking at the time of final bids by license during stage 3. There was a slight tendency for larger licenses to close earlier. However, the association is weaker when one restricts attention to stage 3. Both the bidding behavior and the time of closure by license suggest that bidders had much more flexibility in stage 3 than in a sequence of auctions from largest to smallest.

The problems of a long stage 3 in the MTA auction were reduced in the last three auctions by adjusting the activity rule. In the C-block, the required activity in stage 1 was increased from 33% to 60% and the activity in stage 2 from 67% to 80%. This forces more of the sorting to occur in stages 1 and 2, and yet still give the bidders substantial flexibility in these early stages. In addition, the FCC reduced the stage 3 activity requirement from 100% to 95%, increasing flexibility in stage 3. Similar, activity requirements were used in the MDS and SMR auctions.

A further problem with a low activity requirement is that it can increase the possibility of successful tacit collusion. With an activity requirement of 1/3, bidders can make modest demands without incurring the cost of a loss in eligibility. Unilateral cooperative reductions in demand are possible without losing the ability to punish if reciprocal reductions are not made by others. With a 100% activity requirement, modest demands are only possible with a loss of eligibility.

## 9 Conclusion

The FCC made a bold decision in settling on the simultaneous multiple-round auction to award the PCS licenses. Although this auction form had theoretical virtues, it was unproven. The easy decision would have been to adopt a traditional design, such as a sequential oral auction. Instead, the FCC chose to innovate. After careful study, the FCC began testing and fine-tuning the design with the auction of nationwide and regional narrowband licenses. These first two auctions proved remarkably successful. The theoretical virtues of the design became practical realities. Bidders moved easily among license combinations as prices adjusted. This movement was unhampered by activity requirements in the nationwide auction and only slightly constrained in the regional auction. There was a strong tendency for prices of similar licenses to sell for similar prices. Finally, the license assignments satisfied technical efficiency. When bidders won multiple bands, the bands were adjacent; when bidders won multiple regions, the regions were adjacent and on the same band.

Armed with these early successes, the FCC pushed forward with the MTA broadband PCS auction, the largest auction ever. Although this auction did not share the early aggressive behavior seen in the narrowband auctions, revenues increased steadily throughout the auction. Despite a restrictive activity requirement in the final stage, bidders managed to shift among licenses in response to price changes and build sensible aggregations. Competition heated up in the final stage, suggesting that the auction did identify an efficient allocation through escalating prices. Nonetheless, because of bidder alliances, competition was limited in several markets. Future auctions may benefit from restricting alliances among major firms.

The C-block, MDS, and SMR auctions demonstrated the feasibility of the simultaneous multiple-round auction even with hundreds of bidders and licenses. These auctions required about 80 days of bidding — a relatively short period to determine an assignment of this complexity.

The success of these auctions does not imply that alternative designs would be less successful or that success is assured in future auctions. Although the early evidence is encouraging, there is still much to learn about auctions in this complex setting. One thing is certain: the assignment of licenses by auction is a huge improvement over allocation by lottery or comparative hearings. Market competition is putting the licenses in the hands of those companies best able to use them. Firms, consumers, and taxpayers all benefit.

## References

Ashenfelter, Orley (1989), "How Auctions Work for Wine and Art," *Journal of Economic Perspectives*, 3, 23-26.

Ausubel, Lawrence M. and Peter C. Cramton (1996), "Demand Reduction and Inefficiency in Multi-Unit Auctions," Working Paper, University of Maryland.

Ausubel, Lawrence M., Peter Cramton, R. Preston McAfee, and John McMillan (1996), "Synergies in Wireless Telephony: Evidence from the MTA Auction," Working Paper, University of Maryland.

Avery, Christopher (1994), "Strategic Jump Bidding in an English Auction," Working Paper, Kennedy School of Government, Harvard University.

Ayres, Ian and Peter Cramton (1996), "Pursuing Deficit Reduction Through Diversity: A Case Study of How Affirmative Action at the FCC Increased Auction Competition," *Stanford Law Review*, forthcoming.

Ballard, Charles L., John B. Shoven, and John Whalley (1985), "General Equilibrium Computations of the Marginal Welfare Costs of Taxes in the United States," *American Economic Review*, 85, 128-138.

Banks, Jeffrey S., John O. Ledyard, and David P. Porter (1989), "Allocating Uncertain and Unresponsive Resources: An Experimental Approach," *Rand Journal of Economics*, 20, 1-22.

Bykowsky, Mark M., Robert J. Cull, and John O. Ledyard (1995), "Mutually Destructive Bidding: The FCC Auction Design Problem," Working Paper, CalTech.

Chakravorti, Bhaskar, William W. Sharkey, Yossef Spiegel, and Simon Wilkie (1995), "Auctioning the Airwaves: The Contest for Broadband PCS Spectrum," *Journal of Economics and Management Strategy*, 4, 345-373.

Cramton, Peter (1995), "Money Out of Thin Air: The Nationwide Narrowband PCS Auction," *Journal of Economics and Management Strategy*, 4, 267-343.

Engelbrecht-Wiggans, Richard and Charles M. Kahn (1995), "Multi-Unit Auctions with Uniform Prices," Working Paper, University of Illinois.

Federal Communications Commission (1994), *Fifth Report and Order*, FCC 94-178, Washington, DC.

Federal Communications Commission (1994), *Third Report and Order*, FCC 94-98, Washington, DC.

Gandal, Neil (1995), "Sequential Auctions of Interdependent Objects: Israeli Cable Television Licenses," Working Paper, Tel-Aviv University.

Maskin, Eric S. and John G. Riley (1984), "Optimal Auctions with Risk Averse Buyers," *Econometrica*, 52, 1473-1518.

Maskin, Eric and John Riley (1995), "Asymmetric Auctions," Working Paper, UCLA.

Matthews, Steven A. (1983), "Selling to Risk Averse Buyers with Unobservable Tastes," *Journal of Economic Theory*, 30, 370-400.

McAfee, R. Preston and John McMillan (1987), "Auctions and Bidding," *Journal of Economic Literature*, 25, 699-738.

McAfee, R. Preston and John McMillan (1996), "Analyzing the Airwaves Auction," *Journal of Economic Perspectives*, 10, 159-176.

McAfee, R. Preston and Daniel Vincent (1993), "The Declining Price Anomaly," *Journal of Economic Theory*, 60, 191-212.

McMillan, John (1994), "Selling Spectrum Rights," *Journal of Economic Perspectives*, 8, 145-162.

Milgrom, Paul R. (1987), "Auction Theory," in Truman Bewley (ed), *Advances in Economic Theory - Fifth World Congress*, Cambridge, England: Cambridge University Press.

Milgrom, Paul (1995), *Auction Theory for Privatization*, forthcoming, Cambridge, England: Cambridge University Press.

Milgrom, Paul R. and Robert J. Weber (1982), "A Theory of Auctions and Competitive Bidding," *Econometrica*, 50, 1089-1122.

Myerson, Roger B. (1981), "Optimal Auction Design," *Mathematics of Operations Research*, 6, 58-73.

Rothkopf, Michael H. and Ronald M. Harstad (1990), "Reconciling Efficiency Arguments in Taxation and Public Sector Resource Leasing," Working Paper, Rutgers University.

Rothkopf, Michael H., Ronald M. Harstad, and Yuhong Fu (1996), "When Does it Pay for a Bid Taker to Subsidize Inefficient Bidders?" Working Paper, Rutgers University.

Rothkopf, Michael H., Aleksandar Pekec, and Ronald M. Harstad (1995), "Computationally Manageable Combinatorial Auctions," Working Paper, Rutgers University.

Salant, David J. (1995), "Up in the Air: GTE's Experience in the MTA Auctions for PCS Licenses," Working Paper, Charles River Associates, Boston, MA.

## Table 1

### Final Outcome in Nationwide Narrowband PCS Auction (Round 47)

| Frequency Block | License Type (kHz) | Round of Final Bid | Winning Firm | Winning Bid ($M) | Price ($/MHz-pop) |
|---|---|---|---|---|---|
| 1 | 50/50 | 37 | PageNet | 80.0 | 3.17 |
| 2 | 50/50 | 37 | PageNet | 80.0 | 3.17 |
| 3 | 50/50 | 33 | McCaw | 80.0 | 3.17 |
| 4 | 50/50 | 33 | McCaw | 80.0 | 3.17 |
| 5 | 50/50 | 37 | Mtel | 80.0 | 3.17 |
| 6 | 50/12.5 | 24 | AirTouch | 47.0 | 2.98 |
| 7 | 50/12.5 | 25 | BellSouth | 47.5 | 3.01 |
| 8 | 50/12.5 | 24 | Mtel | 47.5 | 3.01 |
| 10 | 50 | 45 | PageNet | 37.0 | 2.93 |
| 11 | 50 | 46 | PageMart | 38.0 | 3.01 |
| Total | 500/287.5 | | | 617.0 | 3.10 |

Note: Block 9 was a Pioneer's Preference award to Mtel for $33.3 million.

## Table 2

### Final Outcome in Regional Narrowband PCS Auction (Round 105)

| Freq Block | Type (kHz) | *Winning Bidder by Region* | | | | | *Winning Bid ($M) by Region* | | | | | Block Total | Premium Over Nationwide Auction |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Northeast | South | Midwest | Central | West | Northeast | South | Midwest | Central | West | | |
| 1 | 50/50 | <------PageMart won all regions------> | | | | | 17.5 | 18.4 | 16.8 | 17.3 | 22.5 | 92.6 | 15.7% |
| 2* | 50/50 | <------PCS Development won all regions------> | | | | | 14.9 | 18.8 | 17.4 | 17.1 | 22.8 | 90.9 | 13.7% |
| 3 | 50/12 | <------MobileMedia won all regions------> | | | | | 9.5 | 11.8 | 9.3 | 8.3 | 14.9 | 53.7 | 13.4% |
| 4 | 50/12 | <------Advanced Wireless won all regions------> | | | | | 8.9 | 11.5 | 10.1 | 8.8 | 14.3 | 53.6 | 13.3% |
| 5 | 50/12 | AirTouch | InstaCheck | Ameritech | AirTouch | AirTouch | 8.7 | 8.0 | 9.5 | 8.3 | 14.3 | 48.7 | 2.9% |
| 6* | 50/12 | Shearing | Shearing | Shearing | Benbow | Benbow | 10.3 | 11.3 | 10.3 | 10.5 | 10.9 | 53.2 | 12.3% |
| | | | | | | Region Total | 69.7 | 79.8 | 73.3 | 70.3 | 99.7 | 392.7 | 12.4% |

| Freq Block | Type (kHz) | *Round of Final Bid by Region* | | | | | *Price ($/MHz-pop) by Region* | | | | | Block Average | Woman/Minority Effective Discount |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Northeast | South | Midwest | Central | West | Northeast | South | Midwest | Central | West | | |
| 1 | 50/50 | 99 | 92 | 101 | 91 | 83 | 3.39 | 3.55 | 3.23 | 3.52 | 4.72 | 3.67 | |
| 2* | 50/50 | 55 | 93 | 102 | 92 | 84 | 2.87 | 3.62 | 3.33 | 3.48 | 4.77 | 3.60 | 1.8% |
| 3 | 50/12 | 103 | 90 | 98 | 7 | 75 | 2.93 | 3.64 | 2.85 | 2.68 | 4.98 | 3.40 | |
| 4 | 50/12 | 58 | 89 | 100 | 77 | 73 | 2.77 | 3.56 | 3.09 | 2.86 | 4.79 | 3.40 | |
| 5 | 50/12 | 42 | 104 | 64 | 78 | 74 | 2.69 | 2.47 | 2.92 | 2.69 | 4.79 | 3.09 | |
| 6* | 50/12 | 56 | 48 | 58 | 45 | 103 | 3.17 | 3.48 | 3.15 | 3.41 | 3.66 | 3.37 | -2.2% |
| | | | | | | Region Average | 3.00 | 3.42 | 3.13 | 3.17 | 4.64 | 3.46 | |

*Woman/minority bidders get a 40% bidding credit on blocks 2 and 6. All amounts are net of the credit.

## Table 3

## Final Outcome by Market in MTA Broadband PCS Auction (Round 112)

| | | Pops | Round | | Winning Bidder | | Marginal | Bid ($M) | | Price ($/pop) | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| MTA | Market | (M) | A | B | A | B | Bidder | A | B | A | B |
| 1 | New York | 26.4 | * | 74 | Omni | WirelessCo | Alaacr | 347.5 | 442.7 | 13.16 | 16.76 |
| 2 | Los Angeles | 19.1 | * | 82 | Cox | PacTel | Alaacr | 251.9 | 493.5 | 13.16 | 25.78 |
| 3 | Chicago | 12.1 | 75 | 77 | AT&T | PrimeCo | WirelessCo | 372.8 | 385.1 | 30.88 | 31.90 |
| 4 | San Francisco | 11.9 | 98 | 97 | WirelessCo | PacTel | AmerPort | 206.5 | 202.2 | 17.37 | 17.00 |
| 5 | Detroit | 10.0 | 36 | 83 | AT&T | WirelessCo | AmerPort | 81.2 | 86.1 | 8.12 | 8.61 |
| 6 | Charlotte | 9.8 | 39 | 41 | AT&T | BellSouth | CCI | 66.6 | 70.9 | 6.83 | 7.27 |
| 7 | Dallas | 9.7 | 100 | 99 | PrimeCo | WirelessCo | Alaacr | 87.5 | 88.4 | 9.03 | 9.12 |
| 8 | Boston | 9.5 | 50 | 57 | AT&T | WirelessCo | Boston | 121.7 | 127.1 | 12.87 | 13.44 |
| 9 | Philadelphia | 8.9 | 36 | 37 | AT&T | PhillieCo | GTE | 81.0 | 85.0 | 9.07 | 9.52 |
| 10 | Washington | 7.8 | * | 77 | APC | AT&T | AmerPort | 102.3 | 211.8 | 13.16 | 27.23 |
| 11 | Atlanta | 6.9 | 89 | 87 | AT&T | GTE | Powertel | 198.4 | 184.7 | 28.58 | 26.60 |
| 12 | Minneapolis | 6.0 | 101 | 88 | WirelessCo | AmerPort | Continental | 39.7 | 36.6 | 6.63 | 6.11 |
| 13 | Tampa | 5.4 | 98 | 85 | AmerPort | PrimeCo | WirelessCo | 89.8 | 99.3 | 16.57 | 18.33 |
| 14 | Houston | 5.2 | 110 | 79 | AmerPort | PrimeCo | WirelessCo | 83.9 | 82.7 | 16.16 | 15.93 |
| 15 | Miami | 5.1 | 88 | 86 | WirelessCo | PrimeCo | GTE | 131.7 | 126.0 | 25.64 | 24.53 |
| 16 | Cleveland | 4.9 | 86 | 87 | Ameritech | AT&T | AmerPort | 87.0 | 85.9 | 17.59 | 17.36 |
| 17 | New Orleans | 4.9 | 99 | 97 | WirelessCo | PrimeCo | Powertel | 93.9 | 89.5 | 19.07 | 18.17 |
| 18 | Cincinnati | 4.7 | 87 | 111 | AT&T | GTE | WirelessCo | 41.9 | 42.7 | 8.89 | 9.06 |
| 19 | St. Louis | 4.7 | 91 | 92 | AT&T | WirelessCo | PrimeCo | 118.8 | 114.3 | 25.48 | 24.51 |
| 20 | Milwaukee | 4.5 | 111 | 98 | WirelessCo | PrimeCo | AT&T | 85.0 | 86.0 | 18.73 | 18.94 |
| 21 | Pittsburgh | 4.1 | 79 | 110 | WirelessCo | AmerPort | CCI | 28.7 | 31.7 | 7.00 | 7.72 |
| 22 | Denver | 3.9 | 109 | 110 | WirelessCo | GTE | AmerPort | 64.4 | 64.5 | 16.60 | 16.62 |
| 23 | Richmond | 3.8 | 58 | 52 | AT&T | PrimeCo | CCI | 33.7 | 33.0 | 8.75 | 8.59 |
| 24 | Seattle | 3.8 | 101 | 100 | GTE | WirelessCo | AmerPort | 106.4 | 105.2 | 27.79 | 27.48 |
| 25 | Puerto Rico | 3.6 | 46 | 47 | AT&T | Centen | PrimeCo | 56.9 | 54.7 | 15.70 | 15.09 |
| 26 | Louisville | 3.6 | 104 | 106 | AT&T | WirelessCo | PrimeCo | 49.3 | 46.6 | 13.85 | 13.10 |
| 27 | Phoenix | 3.5 | 95 | 96 | AT&T | WirelessCo | GTE | 78.3 | 75.6 | 22.32 | 21.54 |
| 28 | Memphis | 3.5 | 89 | 87 | Powertel | SWBell | WirelessCo | 43.2 | 43.2 | 12.46 | 12.46 |
| 29 | Birmingham | 3.2 | 84 | 85 | WirelessCo | Powertel | AT&T | 35.6 | 35.3 | 10.97 | 10.87 |
| 30 | Portland | 3.1 | 99 | 98 | Western | WirelessCo | Alaacr | 34.2 | 34.1 | 11.16 | 11.16 |
| 31 | Indianapolis | 3.0 | 80 | 81 | WirelessCo | Ameritech | PrimeCo | 70.4 | 71.1 | 23.34 | 23.56 |
| 32 | Des Moines | 3.0 | 83 | 81 | Western | WirelessCo | MicroLith | 22.1 | 21.0 | 7.35 | 7.00 |
| 33 | San Antonio | 3.0 | 105 | 104 | WirelessCo | PrimeCo | Western | 54.4 | 52.0 | 18.21 | 17.39 |
| 34 | Kansas City | 2.9 | 92 | 110 | WirelessCo | AmerPort | GTE | 23.6 | 23.6 | 8.11 | 8.10 |
| 35 | Buffalo | 2.8 | 81 | 82 | WirelessCo | AT&T | PCSAmer | 18.9 | 19.9 | 6.80 | 7.15 |
| 36 | Salt Lake City | 2.6 | 104 | 105 | Western | WirelessCo | GTE | 45.8 | 46.2 | 17.82 | 17.95 |
| 37 | Jacksonville | 2.3 | 110 | 108 | Powertel | PrimeCo | GTE | 46.0 | 44.5 | 20.22 | 19.56 |
| 38 | Columbus | 2.1 | 101 | 102 | AT&T | AmerPort | WirelessCo | 22.3 | 22.2 | 10.39 | 10.34 |
| 39 | El Paso | 2.1 | 89 | 88 | Western | AT&T | PCSAmer | 8.6 | 8.6 | 4.08 | 4.08 |
| 40 | Little Rock | 2.1 | 99 | 98 | SWBell | WirelessCo | PCSAmer | 12.7 | 12.3 | 6.21 | 6.01 |
| 41 | Oklahoma | 1.9 | 111 | 81 | Western | WirelessCo | PCSAmer | 11.1 | 13.1 | 5.92 | 7.00 |
| 42 | Spokane | 1.9 | 50 | 86 | Poka | WirelessCo | Alaacr | 5.7 | 6.2 | 3.05 | 3.32 |
| 43 | Nashville | 1.8 | 86 | 87 | WirelessCo | AT&T | PrimeCo | 16.4 | 15.8 | 9.26 | 8.95 |
| 44 | Knoxville | 1.7 | 80 | 82 | AT&T | BellSouth | PCSAmer | 10.6 | 11.1 | 6.18 | 6.47 |
| 45 | Omaha | 1.7 | 65 | 80 | AT&T | Cox | CCI | 4.6 | 5.1 | 2.80 | 3.06 |
| 46 | Wichita | 1.1 | 65 | 27 | AT&T | WirelessCo | MicroLith | 4.4 | 4.9 | 3.91 | 4.36 |
| 47 | Honolulu | 1.1 | 108 | 107 | Western | PrimeCo | AmerPort | 22.4 | 21.7 | 20.18 | 19.56 |
| 48 | Tulsa | 1.1 | 106 | 105 | SWBell | WirelessCo | Western | 17.6 | 16.8 | 16.02 | 15.32 |
| 49 | Alaska | 0.6 | 111 | 89 | AmerPort | GCI | Western | 1.0 | 1.7 | 1.82 | 3.00 |
| 50 | Guam | 0.2 | 67 | 103 | Poka | AmerPort | PCSAmer | 0.1 | 0.1 | 0.61 | 0.81 |
| 51 | Amer Samoa | 0.0 | 106 | 108 | SSeas | ComIntl | AmerPort | 0.2 | 0.2 | 4.57 | 4.85 |
| | Total | 252.6 | | | | | | 7,736.0 | | 15.54 | |

Population is from 1990 US Census.

*In NY, LA, and Washington, band A is Pioneer's Preference award with price based on GATT formula.

## Table 4

## Final Outcome by Bidder in MTA Broadband PCS Auction (Round 112)

| Company | Upfront Payment ($M) | Initial Eligiblity (M pops) | *Number of Markets* |  |  | *Population Coverage (M)* |  |  | Spectrum Won (%) | Winning Bids ($M) | Average Price ($/pop) |
|---|---|---|---|---|---|---|---|---|---|---|---|
|  |  |  | Won | Marginal | Total | Won | Marginal | Total |  |  |  |
| WirelessCo | 118 | 197 | 29 | 6 | 35 | 145 | 33 | 178 | 32 | 2,110 | 14.56 |
| AT&T | 78 | 131 | 21 | 2 | 23 | 107 | 8 | 115 | 24 | 1,684 | 15.73 |
| PCS PrimeCo | 55 | 91 | 11 | 5 | 16 | 57 | 17 | 74 | 13 | 1,107 | 19.36 |
| American Portable | 20 | 34 | 8 | 8 | 16 | 26 | 43 | 70 | 6 | 289 | 10.91 |
| Alaacr | 33 | 55 |  | 5 | 5 |  | 60 | 60 |  |  |  |
| GTE | 50 | 83 | 4 | 6 | 10 | 19 | 25 | 45 | 4 | 398 | 20.56 |
| PacTel | 56 | 93 | 2 |  | 2 | 31 |  | 31 | 7 | 696 | 22.41 |
| Powertel PCS | 17 | 28 | 3 | 2 | 5 | 9 | 12 | 21 | 2 | 124 | 13.85 |
| CCI Data | 18 | 30 |  | 4 | 4 |  | 19 | 19 |  |  |  |
| Western PCS | 10 | 17 | 6 | 3 | 9 | 14 | 5 | 18 | 3 | 144 | 10.50 |
| BellSouth | 7 | 11 | 2 |  | 2 | 11 |  | 11 | 3 | 82 | 7.15 |
| PCS America | 6 | 10 |  | 6 | 6 |  | 11 | 11 |  |  |  |
| Boston PCS | 6 | 9 |  | 1 | 1 |  | 9 | 9 |  |  |  |
| PhillieCo* | 5 | 9 | 1 |  | 1 | 9 |  | 9 | 2 | 85 | 9.52 |
| Ameritech | 5 | 8 | 2 |  | 2 | 8 |  | 8 | 2 | 158 | 19.85 |
| Southwestern Bell | 17 | 29 | 3 |  | 3 | 7 |  | 7 | 1 | 73 | 11.11 |
| Continental | 4 | 6 |  | 1 | 1 |  | 6 | 6 |  |  |  |
| Micro Lithography | 2 | 3 |  | 2 | 2 |  | 4 | 4 |  |  |  |
| Centennial Cellular | 2 | 4 | 1 |  | 1 | 4 |  | 4 | 1 | 55 | 15.09 |
| Poka Lambro | 2 | 3 | 2 |  | 2 | 2 |  | 2 | 0 | 6 | 2.84 |
| Cox Cable* | 3 | 6 | 1 |  | 1 | 2 |  | 2 | 0 | 5 | 3.06 |
| GCI | 1 | 2 | 1 |  | 1 | 1 |  | 1 | 0 | 2 | 3.00 |
| Com. International | 0 | 0 | 1 |  | 1 | 0 |  | 0 | 0 | 0 | 4.85 |
| South Seas Satellite | 0 | 0 | 1 |  | 1 | 0 |  | 0 | 0 | 0 | 4.57 |
| Cleveland PCS | 3 | 5 |  |  |  |  |  |  |  |  |  |
| Century | 2 | 4 |  |  |  |  |  |  |  |  |  |
| Comcast* | 1 | 2 |  |  |  |  |  |  |  |  |  |
| Satellite Broadcast | 0 | 1 |  |  |  |  |  |  |  |  |  |
| Data Link One | 0 | 0 |  |  |  |  |  |  |  |  |  |
| Windsong | 0 | 0 |  |  |  |  |  |  |  |  |  |
| Total | 522 | 871 | 99 | 51 | 150 | 452 | 253 | 704 | 100 | 7,019 | 15.54 |

Note: Sorted by population coverage of markets in which bidder either won or was marginal (last to drop out).
* WirelessCo partner. WirelessCo got an additional 37.5 million in coverage from partnership agreements.

## Table 5

## Bidder Types and Strategies

| | Price Influence* (M pops) | Issues and Strategy |
|---|---|---|
| _National bidders (all strong)_ | | |
| WirelessCo** | 189 | Most vulnerable from value-seeking bidders, since budget constrained. Time attacks in major markets. |
| AT&T | 115 | Mostly sincere with deep pockets. Avoid competition with PrimeCo. |
| PCS PrimeCo | 74 | Moderate under bidding. Deep pockets. Avoid competition with AT&T. Scale back demands to keep prices low. |
| _Value-seeking bidders_ | | |
| *Moderate* | | |
| American Portable | 70 | Look for value. Get concessions from national bidders or impose costs. Maintain flexibility. |
| Alaacr | 60 | Look for value in major markets. |
| *Weak* | | |
| CCI Data | 19 | Look for value. Limited budget. |
| PCS America | 11 | Look for value in small markets. Small budget. |
| Micro Lithography | 4 | " |
| Poka Lambro | 2 | " |
| _Regional bidders_ | | |
| *Strong* | | |
| GTE | 45 | Wait and see. Avoid markets of main interest until late in auction. Budget constrained. |
| PacTel | 31 | Sincere bidding in primary markets. Scale back early in secondary markets. |
| BellSouth | 11 | Sincere bidding in primary markets. |
| Ameritech | 8 | " |
| *Moderate* | | |
| Powertel PCS | 21 | Sincere bidding in primary markets. Modest budget. |
| Western PCS | 18 | " |
| Southwestern Bell | 7 | " |
| *Weak* | | |
| Boston PCS | 9 | Sincere bidding in single market until too high. |
| Continental | 6 | |
| | | Small budget. Switch to cheap markets if prices too high in primary markets. |
| Centennial Cellular | 4 | Sincere bidding in single market. |
| GCI | 1 | Wait and see before bidding in primary market. |
| Com. International | 0 | Sincere bidding in single market. |
| South Seas Satellite | 0 | " |
| *Very weak* | | |
| Cleveland PCS | | Sincere bidding in single market until too high. |
| Century | | " |
| Satellite Broadcast | | " |
| Data Link One | | " |
| Windsong | | " |

*Population coverage of markets in which bidder either won or was marginal (last to drop out).

**Includes partners: PhillieCo, Cox Cable, and Comcast.

## Table 6

## Bid Withdrawals in MTA Broadband PCS Auction

| Round | License | Market | Bidder | Winning Bidder | Bid ($M) | Winning Bid ($M) | Penalty ($M) | My Explanation |
|---|---|---|---|---|---|---|---|---|
| 18 | 9 B | Philadelphia | SWBell | PhillieCo | 35.7 | 85.0 | | Signal drop in eligibility |
| 27 | 41 B | Oklahoma | Alaacr | WirelessCo | 3.1 | 13.1 | | Changed mind about bid |
| 66 | 48 A | Tulsa | Western | SWBell | 11.9 | 17.6 | | Increase flexibility in next round |
| 81 | 14 A | Houston | WirelessCo | AmerPort | 87.9 | 83.9 | | Maintain eligibility |
| 81 | 15 B | Miami | WirelessCo | PrimeCo | 119.4 | 126.0 | | Maintain eligibility |
| 82 | 49 A | Alaska | Western | AmerPort | 1.0 | 1.0 | | Maintain eligibility |
| 87 | 12 B | Minneapolis | WirelessCo | AmerPort | 38.4 | 36.6 | 1.8 | Drop double bid used to maintain eligibility |
| 87 | 41 A | Oklahoma | WirelessCo | Western | 13.1 | 11.1 | 2.0 | Drop double bid used to maintain eligibility |
| 88 | 28 A | Memphis | WirelessCo | Powertel | 45.3 | 43.2 | 2.2 | Maintain eligibility |
| 97 | 13 A | Tampa | WirelessCo | AmerPort | 94.3 | 89.8 | 4.5 | Gift for AmerPort to get off San Francisco |
| 97 | 14 A | Houston | WirelessCo | AmerPort | 87.9 | 83.9 | | Gift for AmerPort to get off San Francisco |
| 98 | 38 B | Columbus | WirelessCo | AmerPort | 21.1 | 22.2 | | Maintain eligibility |
| 102 | 18 B | Cincinnati | GTE | GTE | 42.7 | 42.7 | | Increase flexibility in next round |
| 102 | 33 A | San Antonio | Western | WirelessCo | 51.8 | 54.4 | | Maintain eligibility |
| 102 | 49 A | Alaska | AmerPort | AmerPort | 1.3 | 1.0 | 0.3 | Maintain eligibility |
| 104 | 26 B | Louisville | PrimeCo | WirelessCo | 44.4 | 46.6 | | Maintain eligibility |
| 108 | 20 A | Milwaukee | WirelessCo | WirelessCo | 85.0 | 85.0 | | Increase flexibility in next round |
| 108 | 41 A | Oklahoma | WirelessCo | Western | 10.0 | 11.1 | | Reduce penalty |
| 109 | 14 A | Houston | WirelessCo | AmerPort | 87.9 | 83.9 | 4.0 | Increase flexibility in next round |
| 109 | 21 B | Pittsburgh | AmerPort | AmerPort | 31.7 | 31.7 | | Increase flexibility in next round |
| 109 | 34 B | Kansas City | AmerPort | AmerPort | 23.6 | 23.6 | | Increase flexibility in next round |
| | | | | | | Total | 14.8 | |

## Table 8

## Comparison of FCC Spectrum Auctions

| | *FCC Spectrum Auction* | | | | | |
|---|---|---|---|---|---|---|
| | *Narrowband PCS* | | *Broadband PCS* | | *MDS* | *SMR* |
| | Nationwide | Regional | MTA (A-B) | BTA (C) | BTA | 900 MHz |
| Number of market areas | 1 | 5 | 51 | 493 | 493 | 51 |
| Number of frequency blocks | 10 | 6 | 2 | 1 | 1 | 20 |
| Number of licenses | 10 | 30 | 99 | 493 | 493 | 1020 |
| Total spectrum (MHz) | 0.7875 | 0.45 | 60 | 30 | | |
| Revenue including pioneer preference ($M) | 650 | 395 | 7,736 | 10,219 | 216 | 312 |
| Average price ($/MHz-pop) | 3.10 | 3.46 | 0.52 | 1.33 | NA | NA |
| Number of bidders | 29 | 28 | 30 | 255 | 155 | 128 |
| Number of winning bidders | 6 | 9 | 18 | 89 | 67 | 80 |
| Correlation between upfront payment and spectrum won | 78% | 83% | 93% | 64% | 63% | 80% |
| Number of rounds | 47 | 105 | 112 | 184 | 181 | 168 |
| Number of days | 5 | 10 | 60 | 84 | 75 | 79 |
| Number of bids | 385 | 738 | 2,268 | 29,865 | 15,417 | 14,931 |
| Bids per license | 38.5 | 24.6 | 22.9 | 60.6 | 31.3 | 14.6 |
| Switch to stage 2 in round | never | 21 | 12 | 58 | 51 | 17 |
| Switch to stage 3 in round | never | 74 | 65 | 70 | 87 | 37 |
| Percent revenue raised in stage 1 | 100% | 80% | 13% | 88% | 44% | 54% |
| Percent revenue raised in stage 2 | 0% | 14% | 52% | 6% | 22% | 10% |
| Percent revenue raised in stage 3 | 0% | 6% | 36% | 7% | 35% | 36% |
| Initial eligibility ratio | 8.8 | 6.1 | 1.9 | 6.7 | 3.6 | 2.4 |
| Eligibility ratio at end of stage 1 | 1.0 | 3.1 | 1.9 | 1.8 | 1.9 | 1.8 |
| Eligibility ratio at end of stage 2 | | 1.5 | 1.5 | 1.3 | 1.3 | 1.4 |
| High bidders at end of stage 1 that eventually win | 100% | 71% | 53% | 60% | 64% | 48% |
| High bidders at end of stage 2 that eventually win | | 71% | 76% | 72% | 79% | 59% |
| Correlation between final prices and prices at end of stage 1 | 100% | 65% | 32% | 87% | 66% | 58% |
| Correlation between final prices and prices at end of stage 2 | | 91% | 83% | 90% | 78% | 69% |
| Licenses with final bids at end of stage 1 | 100% | 3% | 0% | 34% | 15% | 8% |
| Licenses with final bids at end of stage 2 | | 29% | 19% | 57% | 42% | 18% |
| Number of bid withdrawals | 0 | 2 | 21 | 50 | 23 | 64 |
| Bid withdrawal penalties ($M) | 0.0 | 2.1 | 14.8 | 147.3 | 0.1 | 107.5 |

**Figure 1**
**Bidding Activity and Revenue by Round in Nationwide Narrowband Auction**

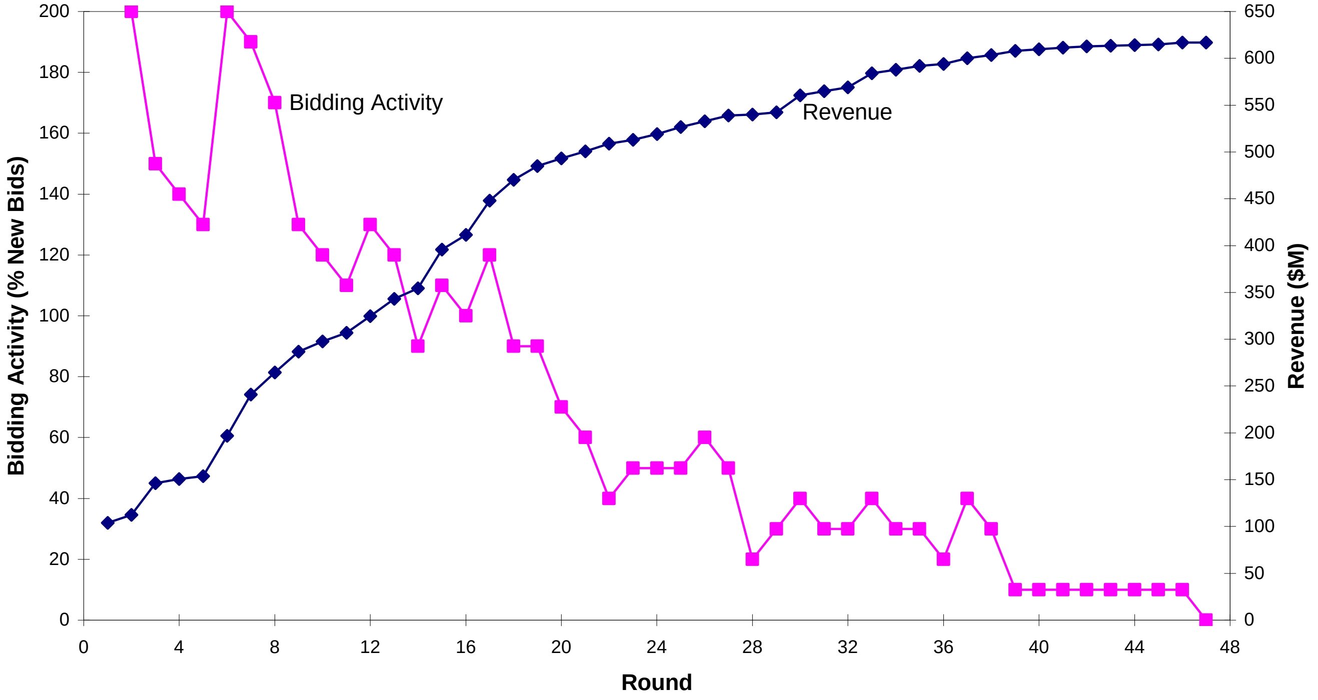


**Figure 2**
**Bidding Activity and Revenue by Round in Regional Narrowband Auction**

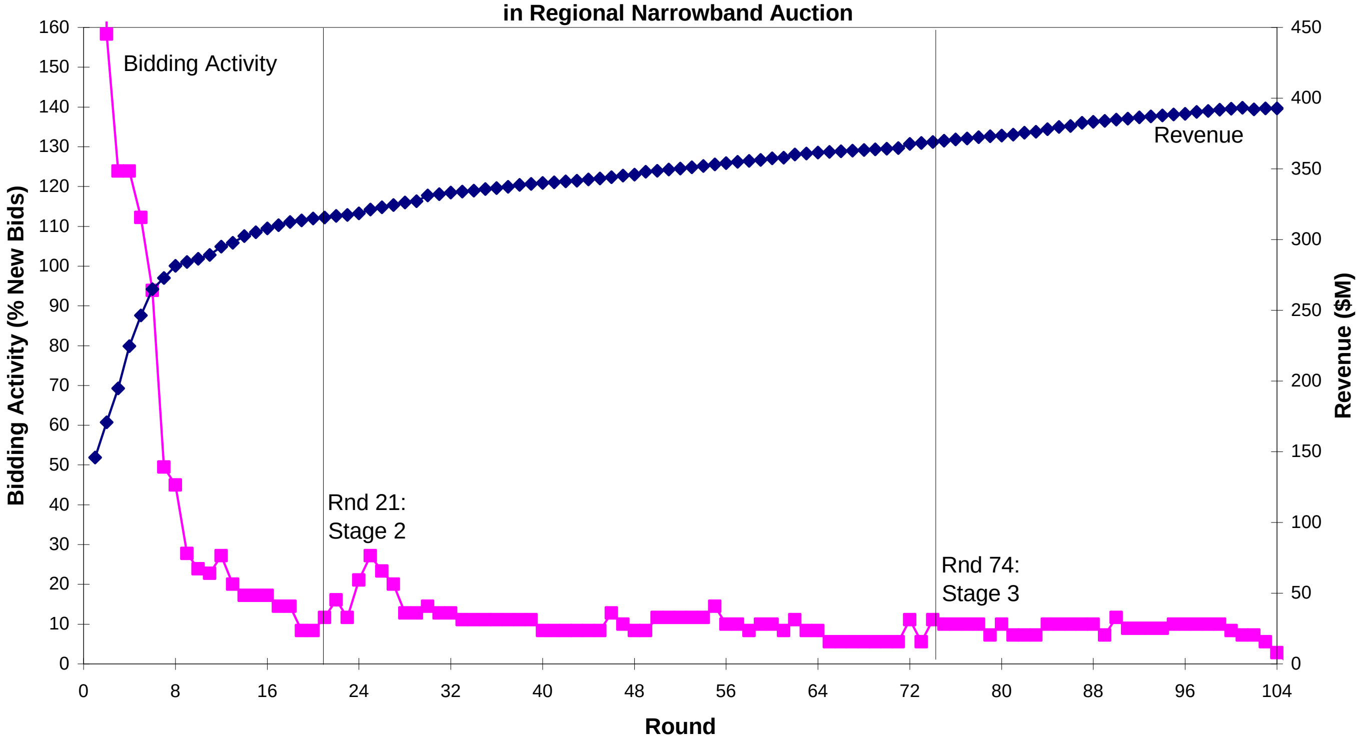


**Figure 3**
**Bidding Activity and Revenue by Round in MTA Broadband Auction**

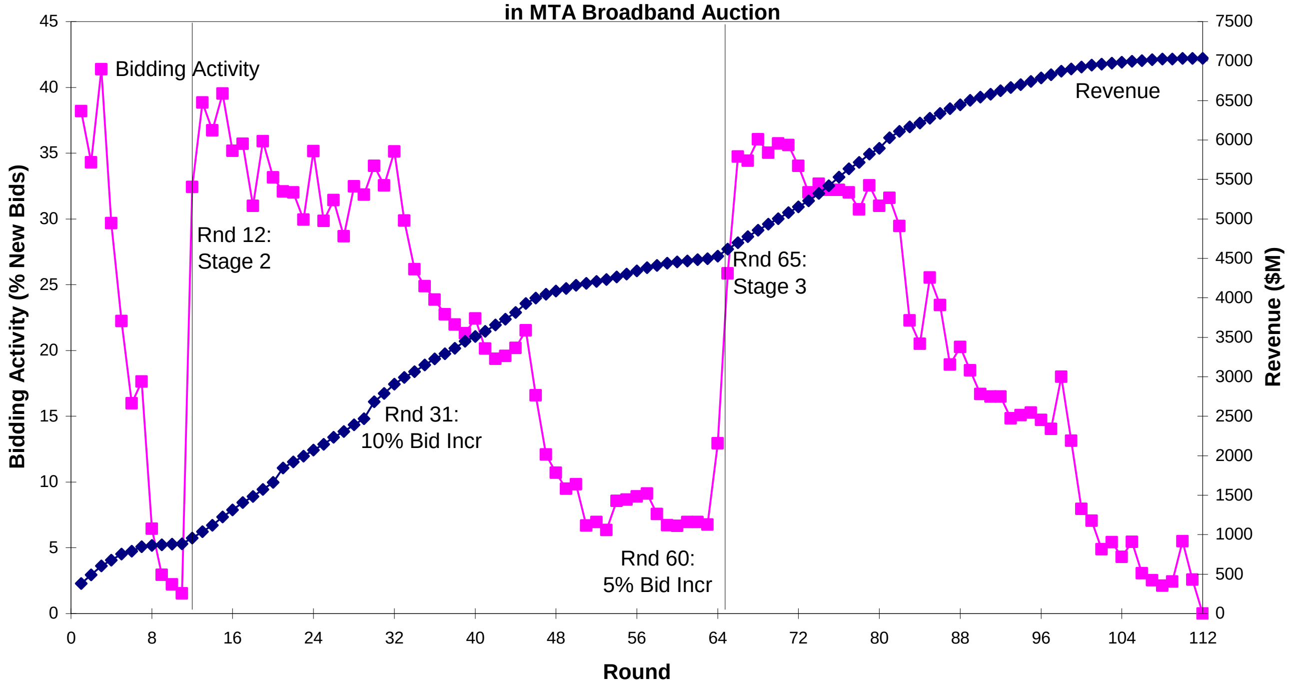
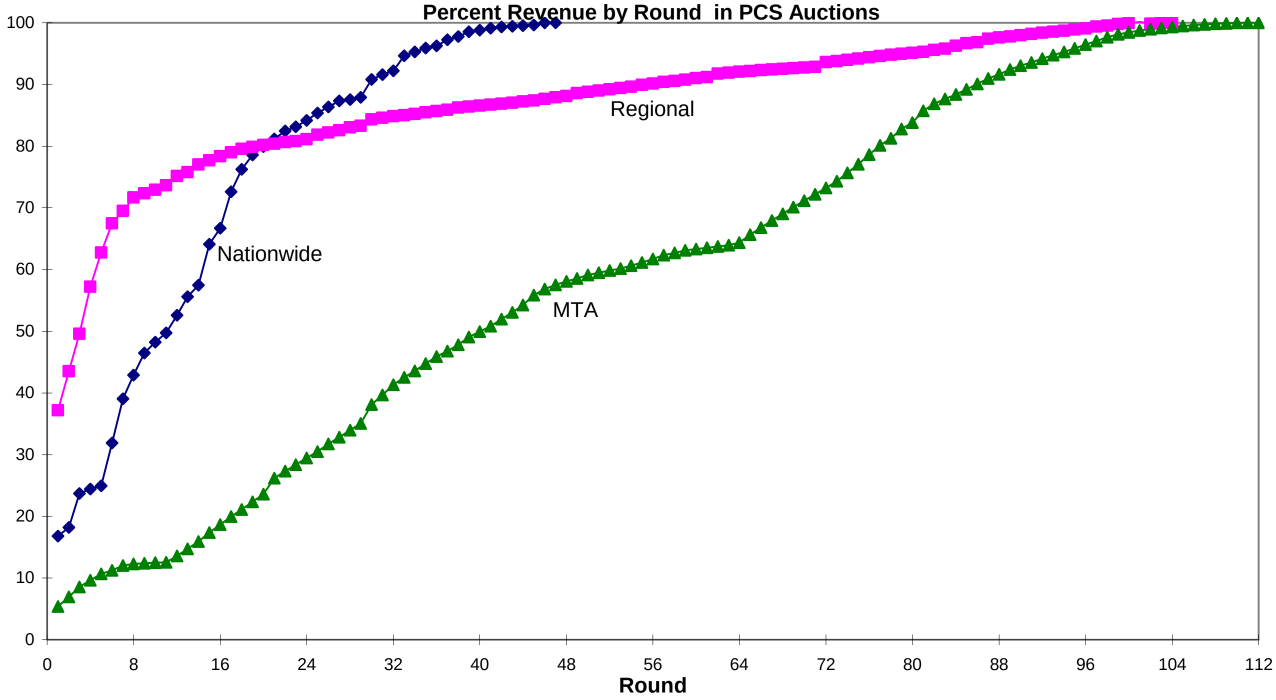
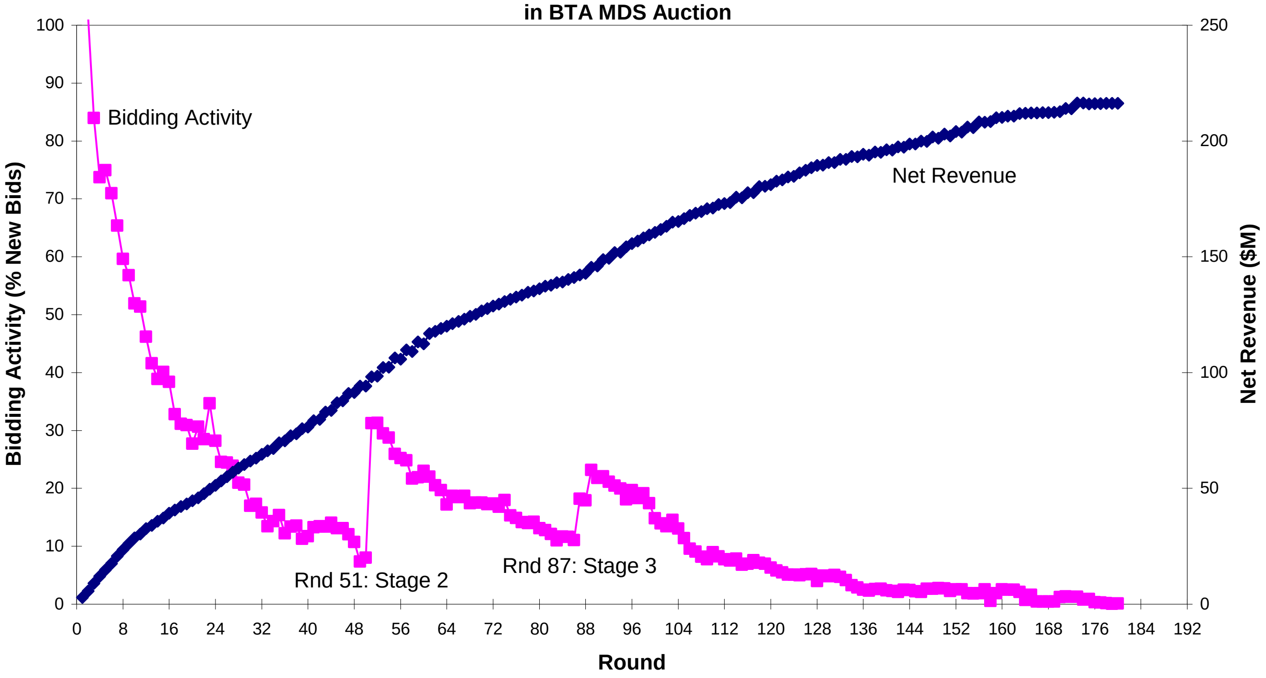


**Figure 4**
**Percent Revenue by Round in PCS Auctions**



## Figure 5
## Bidding Activity and Net Revenue by Round in BTA MDS Auction



## Figure 6
## Bidding Activity and Net Revenue by Round in SMR 900 Auction

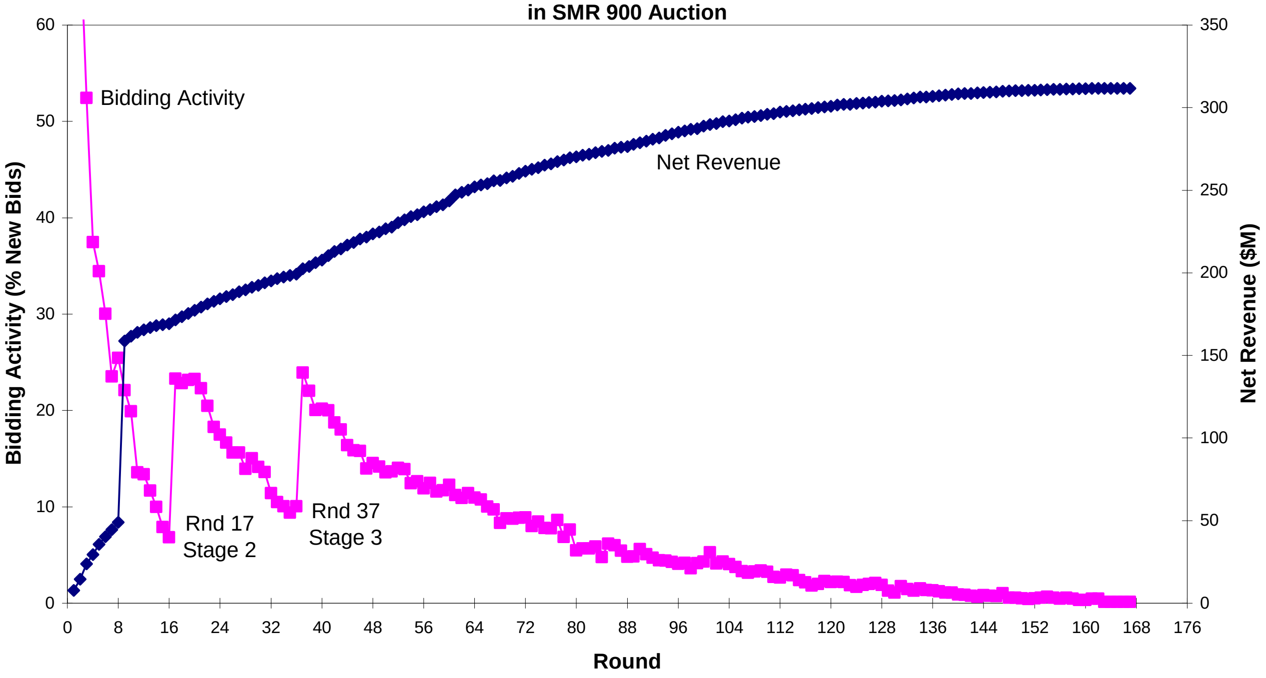


**Figure 7**
**Fraction of Current High Bidders that Win in Market (Pop Weighted) in MTA Auction**

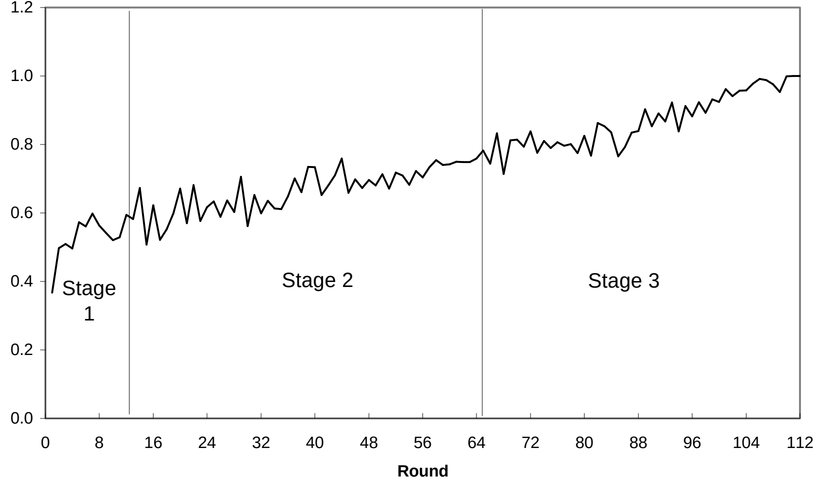


**Figure 8**
**Correlation Between Current and Final Prices in MTA Auction**

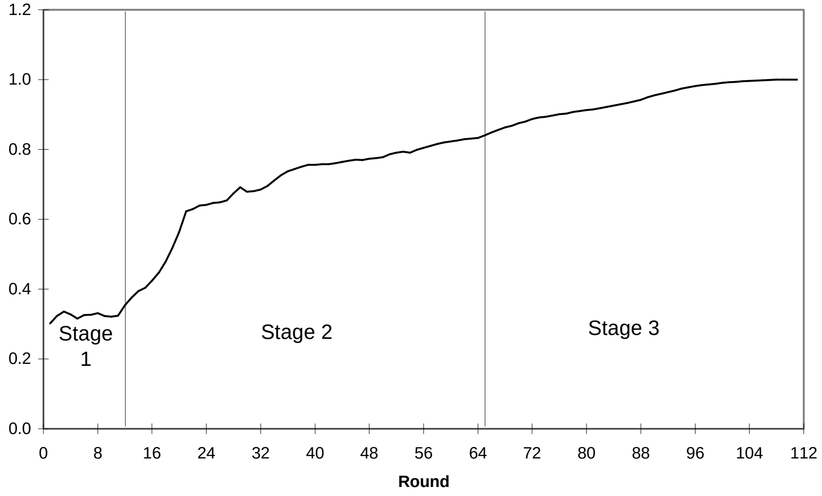


**Figure 9**
**Eligibility Ratio in MTA Auction (Total Eligibility)/(Total Spectrum)**

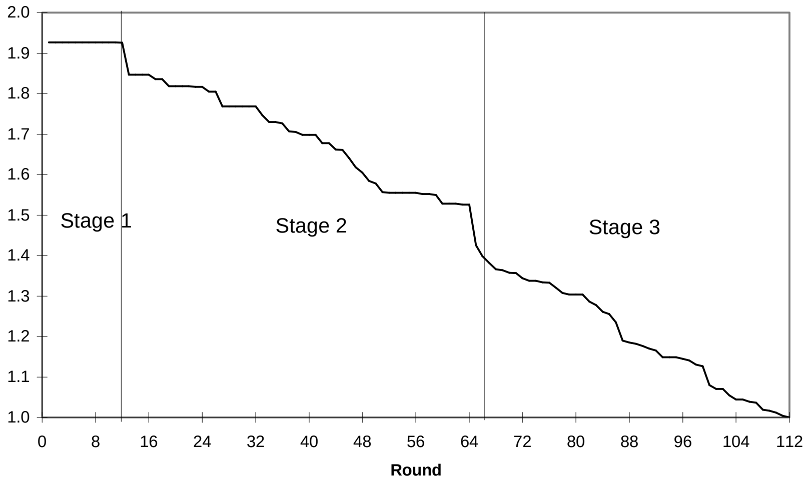


**Figure 10**
**Fraction of Licenses with Final Bid (Pop Weighted) in MTA Auction**