**Analyzing the Airwaves Auction**

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J ust as the Nobel committee was recognizing game theory's role in economics by awarding the 1994 prize to John Nash, John Harsanyi and Reinhard Selten, game theory was being put to its biggest use ever. Billions of dollars worth of spectrum licenses were being sold by the U.S. government, using a novel auction form designed by economic theorists. Suddenly, game theory became news. William Safire in the *New York Times* called it "the greatest auction in history." *The Economist* remarked, "When government auctioneers need worldly advice, where can they turn? To mathematical economists, of course. . . . As for the firms that want to get their hands on a sliver of the airwaves, their best bet is to go out first and hire themselves a good game theorist." *Fortune* said it was the "most dramatic example of game theory's new power. . . . It was a triumph, not only for the FCC and the taxpayers, but also for game theory (and game theorists)." *Forbes* said, "Game theory, long an intellectual pastime, came into its own as a business tool." The *Wall Street Journal* said, "Game theory is hot."[1]

The government auctioned licenses to use the electromagnetic spectrum for personal communications services (PCS): mobile telephones, two-way paging, portable fax machines and wireless computer networks. Thousands of licenses were offered, varying in both geographic coverage and the amount of spectrum covered. The bidders were the local, long-distance and cellular telephone companies, as well as paging and cable television companies and a host of smaller firms. The Federal

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[1] The citations for the quotations in this paragraph are *New York Times*, March, 16, 1995, p. A17; *The Economist*, July 23, 1994, p. 70; *Fortune*, February 6, 1995, p. 36; *Forbes*, July 3, 1995, p. 62; *Wall Street Journal*, February 13, 1995, p. A19.

■ *R. Preston McAfee is Professor of Economics, University of Texas, Austin, Texas. John McMillan is Professor of Economics, Graduate School of International Relations and Pacific Studies, University of California, San Diego, La Jolla, California.*

Communications Commission (FCC) chose an innovative form of auction over the time-tested alternatives (like a sealed-bid auction), because theorists predicted it would induce more competitive bidding and a better match of licenses to firms.

The designing of the spectrum auction has been described in this journal by McMillan (1994).[2] In what follows, we examine how the auction actually worked. We describe the strategies used by the bidders, and analyze the success of the auction in realizing the government's goals. While theory was used in designing the auction, in turn the auction has stimulated further theorizing, as we discuss. We also propose some other potential uses of the auction form that the FCC pioneered.

## The Simultaneous Ascending Auction

In the 1993 legislation authorizing the FCC to hold auctions, Congress charged the FCC with encouraging an "efficient and intensive use of the electromagnetic spectrum." Congress also said the auction should advance various public-policy goals and in particular ensure some licenses went to minority-owned and women-owned firms. Congress said revenue raising was an aim of the auction, but gave it a low priority.

The auction the FCC adopted is a *simultaneous ascending auction*, first proposed by Paul Milgrom and Robert Wilson (consultants for Pacific Telesis) and Preston McAfee (a consultant for AirTouch Communications). Multiple licenses are open for bidding at the same time, and remain open as long as there is some bidding on any of the licenses. Bidding occurs over rounds, with the results of each round announced to the bidders before the start of the next. The auction is run by computer, with on-line bidding.

Many detailed rules are needed to support the broad principles of the simultaneous ascending auction. Months of work by FCC officials (Evan Kwerel's contribution to the design process was crucial) and the theorist-consultants (including John McMillan, who worked for the FCC) went into writing the auction rules to close any gaps that could be exploited by clever bidders: the rules, in FCC (1994), cover more than 130 pages. The most important of these details are the activity rules (devised by Milgrom and Wilson). A bidding firm might play cautiously, waiting to see how the others bid while not revealing its own intentions. If all bid in this way the auction would take inordinately long to close. The activity rules are designed to prevent the bidders from holding back, so the auction proceeds at a reasonable pace. Before the auction, each bidder must specify how many licenses it hopes to win and must post a proportionate bond. A bidder is defined to be active on a particular license if either it has the standing high bid from the previous round

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[2] For more on game theory's role in the design of the FCC auction, see Milgrom (1995). For more on auction performance and bidder strategies, see Cramton (1995a,b) and Salant (1995). On the case for using auctions to assign the spectrum, see McMillan (1995), and on the history and politics of spectrum allocation, see Hazlett (1995).

or it submits an acceptable bid in this round. The auction has three stages, each containing an unspecified number of bidding rounds. In the first stage a bidder must be active on licenses that add up to one-third of its desired total; in the second stage, two-thirds; and in the final stage, 100 percent. If a bidder ever falls short of the required activity level, the number of licenses it is eligible to own shrinks proportionately. There is no prespecified final round; instead, the auction closes when no one wants to continue bidding. Other rules define the size of bid increments, the penalties for bid withdrawal,[3] provisions for waivers from the activity rules, the length of time for a bidding round, and so on.

Why use a simultaneous ascending auction? Why not use the time-tested method, a sequential auction, in which the licenses are simply offered one after the other? Or why not use the quickest method, offering all the licenses simultaneously in a single round of sealed bids? The main reason is that the licenses are interdependent. For most of the licenses there is a close substitute: a twin license that covers the same region and the same amount of spectrum. Licenses are also complementary: a license may be more valuable if the holder also has the license for a contiguous region.

Efficiency in a spectrum auction—which means assigning the licenses to the firms best able to use them—requires that some bidders win multiple licenses, because of the license complementarities. The FCC did not know before the sale how the licenses should be aggregated: partly because the technology was new, but also because different bidders had different, mutually inconsistent preferred aggregations (for various reasons, such as their cellular-telephone holdings and local expertise). The simultaneous ascending auction was designed to let market processes establish the shape of the license aggregations.

Both features of the auction form—the *simultaneous* bids and the *ascending* bids—aid efficiency. The ascending bids let bidders see how highly their rivals value each license and which aggregations they are seeking. By the time equilibrium is approached, each bidding firm knows whether it is likely to be able to construct its preferred aggregation and roughly how much it is going to cost. With all licenses open for bidding simultaneously, a bidder has flexibility to seek whatever license aggregation it wishes, as well as to switch to a back-up aggregation if its first-choice aggregation becomes too expensive.

As well as aiding license aggregation, the ascending bidding, by allowing bidders to respond to each others' bids, diminishes the winner's curse: that is, the tendency for naive bidders to bid up the price beyond the license's actual value, or for shrewd bidders to bid cautiously to avoid overpaying. Also, ascending simultaneous bidding means it is likely that substitute licenses fetch similar prices, because bidders can switch across the substitutes if their bid prices differ, bidding up any lower-priced licenses.

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[3] The withdrawal penalty involved guaranteeing the price bid. If after the license was reoffered, the final price was less than the withdrawn bid, the bidder who withdrew owed a penalty equal to the difference.

The alternative auction forms do not assure either efficient aggregation or that similar items will fetch the same price.[4] A single-round, sealed-bid auction, for example, would almost certainly cause a poor match of licenses to firms. Bidders must bid blind, unable to know how high they must bid to win a particular license. Only by good luck would a bidding firm win all the licenses it needs for an efficient aggregation; bad luck could mean the firm wins more licenses than it needs. Also, the bidders' fear of the winner's curse induces more cautious bidding and lower prices than ascending bids would yield. The risk of winning too many licenses further induces low bidding from budget-constrained bidders. Simultaneous single-round, sealed-bid auctions were used in New Zealand for spectrum licenses and in Australia for satellite-television licenses, with disappointing results: low revenues and inefficient license allocations (McMillan, 1994).

Sequential auctions also have problems. First, identical items can sell for quite different prices: items sold later in the sequence typically fetch less than items sold earlier (Ashenfelter, 1989; McAfee and Vincent, 1993). Second, a firm might bid in a predatory manner, driving early prices unreasonably high to eliminate its budget-constrained rivals from the later bidding (Pitchik and Schotter, 1988). Third, and most important, the sequential form hinders license aggregation. In the early auctions, a firm must bid without knowing whether it will win complementary licenses offered later. Later, a firm may wish to rebid on a license already sold if it discovers it needs that license to complete its set; but in a sequential auction it cannot go back. One of the pitfalls of the sequential auction is shown by the 1981 sale of seven identical licenses to use RCA's communications satellite for cable television broadcasts. Sotheby Parke Bernet ran a sequential auction. The winning bids varied widely. The highest (on the first license sold) was $14.4 million, and the lowest (the sixth license) was $10.7 million.[5] The FCC nullified the auction, saying the procedure was "unjustly discriminatory" in levying different prices for the same service, and ordered RCA to charge the same price to all. The inflexibility of the sequential auction caused the $3.7 million (or 26 percent) price difference. It would not have arisen had a simultaneous ascending auction been used, as price disparities would be bid away.[6]

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[4] There was, however, considerable disagreement among the theorists involved in the design process, based on differing judgments about the sizes of various effects and the workability of the simultaneous ascending auction. Some advocated a sequential auction; others, an auction in which bidders could bid for license combinations, not just single licenses. On this debate, see McMillan's (1994) article in this journal.

[5] The story is told in several places: *PR Newswire*, November 9, 1981; *Christian Science Monitor*, June 29, 1982, p. 11; *Time*, December 13, 1982, p. 148.

[6] Prices sometimes rise rather than fall during a sequential auction. In Israel's 1987–1990 sequential auctions of cable television licenses, Gandel (1994) finds that the prices tended to be higher for licenses auctioned later. The competition seems to have intensified later, because by then some bidders held complementary licenses and so were willing to pay more. If a simultaneous ascending auction had been used instead, the earlier licenses may have been bid higher, and different bidders may have won the later licenses. Whether prices rise or fall, the uncertainty in a sequential auction creates difficulties for bidders, exacerbating the winner's curse and hindering efficient aggregation.

After-market trading of licenses is permitted, subject to FCC approval, and such trading will assist in ultimately producing an efficient allocation of spectrum rights. But it is unrealistic to believe that the after-market can completely solve the allocation problem no matter what the initial allocation—which would mean the auction form would not matter—because it will be far from fully competitive. There will be few buyers and few sellers. Also, the firms possess private information about license values through their knowledge of customers, local conditions and technology. Modern theory shows that private information can hinder efficient trade (Akerlof, 1970; Myerson and Satterthwaite, 1983).

Persuaded of the superiority of the simultaneous ascending auction by the theorists, and of its workability by some experiments, the FCC decided to adopt it. The FCC's courage in using an untried mechanism devised by a set of mathematical economists was rewarded: the simultaneous ascending auction came to be widely regarded as a success.

## Auction Performance

Because of the logistical complexities of running a huge simultaneous auction, not all of the roughly 2,000 licenses were offered for sale at once. The FCC planned five auctions, each in the simultaneous ascending format. Three have been held at the time of this writing. The first two sold narrowband licenses, thin slivers of the spectrum to be used for paging services: nationwide licenses were sold in July 1994 and regional licenses in October 1994, covering 1.2 mHz of spectrum between them. The other auctions offer broadband licenses, which cover a wide enough slice of spectrum to be usable for voice and data mobile communications services. The third and largest auction, which ran from December 1994 to March 1995, sold 60 mHz of spectrum: two 30 mHz broadband licenses covering relatively large geographic areas (the "major trading areas," or MTAs, which divide the United States into 51 regions). The fourth and fifth auctions will each offer broadband licenses covering 30 mHz of spectrum over smaller areas (the "basic trading areas," or BTAs, which divide the United States into 492 regions).

The Office of Management and Budget estimated in 1993 that $10 billion would be paid for the broadband spectrum—enough to make a dent in the budget deficit. The industry's immediate response to this estimate was (possibly strategic) skepticism. BellSouth chairman John Clendenin said, "There is no rational methodology on which that $10 billion was calculated." The government estimate, he asserted, "was sort of pulled out of thin air" (and perhaps he was right). MCI chairman Bert Roberts said, "The government is smoking something to think they are going to get $10 billion for these licenses." As it turned out, however, the government's estimate was low.

"For once, the government is doing a great job of dragging money out of people," said Wayne Perry of McCaw Cellular Communications during the first auction. The two narrowband auctions raised over $1 billion, far more than most

*Table 1*
**Auction Results for Nationwide Narrowband Licenses**

| Licence | Winning Bid ($ millions) | Winning Bidder |
|---|---|---|
| 50/50 kHz | 80.0 | Paging Network of Virginia |
| 50/50 kHz | 80.0 | Paging Network of Virginia |
| 50/50 kHz | 80.0 | KDM Messaging Co. |
| 50/50 kHz | 80.0 | KDM Messaging Co. |
| 50/50 kHz | 80.0 | Nationwide Wireless Network Corp. |
| 50/12.5 kHz | 47.0 | AirTouch Paging |
| 50/12.5 kHz | 47.5 | BellSouth Wireless |
| 50/12.5 kHz | 47.5 | Nationwide Wireless Network Corp. |
| 50 kHz | 37.0 | Paging Network of Virginia |
| 50 kHz | 38.0 | Pagemart II, Inc. |
| Total | 617.0 | |

*Note:* The 50/50 and 50/12.5 licenses each have two separated slices of spectrum, to allow two-way pager communication.
*Source:* FCC.

predictions. Then the broadband MTA auction attracted the big spenders: Wirelessco L.P. (a consortium of the Sprint Corp. with the cable television companies TCI, Comcast and Cox), which bid a total of $2.1 billion; the AT&T Corp., $1.7 billion; PCS Primeco L.P. (a consortium of Bell Atlantic, U.S. West, AirTouch and Nynex), $1.1 billion; and the Pacific Telesis Group (or PacTel), $0.7 billion. Selling half the 120 mHz of broadband spectrum, this auction raised $7.7 billion.[7]

The simultaneous ascending auction should yield similar prices for similar items. Did it? The nationwide narrowband auction priced similar licenses very closely (see Table 1: the five 100 kHz licenses are close substitutes, as are the three 65.5 kHz licenses and the two 50 kHz licenses). In the regional narrowband auction, prices for substitute licenses were similar, though not as close as in the nationwide auction (see Table 2: licenses 1 and 2 are substitutes, as are licenses 3, 4, 5 and 6). A price disparity existed across the two auctions, however: prices in the regional auction were higher than in the earlier nationwide auction (compare the last row of Table 2 with Table 1).

Prices were lower in the broadband MTA auction than in the narrowband auctions. The average broadband price per pop (that is, price per person covered by the license) was $15.51, which meant the price per mHz-pop was just 16 percent

[7] The complete auction data, including round-by-round bids, can be found on the Internet at the FCC web server, www.fcc.gov. The $7.7 billion sum includes the revenue from the licenses awarded as "pioneer preferences." Before the auction the FCC awarded three MTA licenses—New York, Los Angeles and Washington D.C.—to three firms as a reward for developing new technologies. These firms paid concessionary prices based on the winning bids. (The quotations in the paragraph are from *Reuters Financial Report*, October 20, 1993, and *Wall Street Journal*, August 1, 1994, p. A1.)

*Table 2*
**Auction Results for Regional Narrowband Licenses**
*(discounted final prices in millions and winning bidder by region and spectrum block)*

| Region/Block | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| (kHz) | (50/50) | (50/50) | (50/12.5) | (50/12.5) | (50/12.5) | (50/12.5) |
| Northeast | 17.5 | 14.9 | 9.5 | 9.0 | 8.7 | 10.3 |
| | Pagemart | PCSD | Mobile | Am.W. | AirTouch | L.G.S. |
| South | 18.4 | 18.8 | 11.8 | 11.5 | 8.0 | 11.3 |
| | Pagemart | PCSD | Mobile | Am.W. | Instacheck | L.G.S. |
| Midwest | 16.8 | 17.4 | 9.3 | 10.1 | 9.5 | 10.3 |
| | Pagemart | PCSD | Mobile | Am.W. | Ameritech | L.G.S. |
| Central | 17.3 | 17.1 | 8.3 | 8.8 | 8.3 | 10.5 |
| | Pagemart | PCSD | Mobile | Am.W. | AirTouch | Benbow |
| West | 22.6 | 22.8 | 14.9 | 14.3 | 14.3 | 10.9 |
| | Pagemart | PCSD | Mobile | Am.W. | AirTouch | Benbow |
| Total | 92.6 | 90.9 | 53.7 | 53.6 | 48.7 | 53.2 |

*Notes:* Spectrum blocks 1 and 2 consisted of two 50 kHz channels; blocks 3, 4, 5 and 6 consisted of one 50 kHz and one 12.5 kHz channel. Spectrum blocks 2 and 6 had the 40 percent minority/woman credit; the prices shown for these two licenses are net of this discount. "PCSD" is the PCS Development Corp. "Mobile" is Mobilemedia, Inc. "Am.W." is American Wireless Messaging. "L.G.S." is Lisa-Gaye Shearing. *Source:* FCC.

of the narrowband price. The lower prices had several sources. First, the broadband spectrum has intrinsically lower value, as some of it has incumbent users who will have to be moved. Second, the firms had budget constraints, the sums bid being large even for a firm as big as AT&T. Third, the competition was less intense, as the ratio of initially expressed demand to licenses for sale was just two-to-one.

The broadband prices varied greatly from license to license. The winners of the ten largest-population licenses are shown in Table 3. Highest in price per pop were Chicago ($31.90 and $30.88), Atlanta ($28.58 and $26.60) and Seattle ($27.79 and $27.48). Lowest in price per pop were Guam ($0.61 for both licenses) and Alaska ($1.82 and $3.00). Variations in price in part reflect regional variations in predicted demand for PCS services. The profitability of a license varies with income level, population density, predicted population growth and so on. There are also bidder-specific effects, such as home-base advantages for the local Bell companies or the ownership of a cellular license in a neighboring area. Some of the price differences, however, do not seem to be explained by value differences: for example, the Chicago price per pop is nearly twice New York and 20 percent higher than Los Angeles. Few bidders were eligible to bid on some licenses. Chicago was the only license among the top ten for which all three of the big bidders competed: AT&T, Primeco and Wirelessco. Some of the price variations reflect differences in the strength of competition.

Revenue is not the only criterion for evaluating the FCC auctions; it is not even the main goal. Another criterion is whether the auctions generated an economically

**Table 3**

**Auction Results for Broadband MTA Licenses**

*(top 10 licenses, winner and price bid in $ millions)*

| Region/Block | A | | B | |
|---|---|---|---|---|
| New York | ª | | Wirelessco | 443 |
| Los Angeles | ª | | PacTel | 494 |
| Chicago | AT&T | 373 | Primeco | 385 |
| San Francisco | Wirelessco | 207 | PacTel | 202 |
| Detroit | AT&T | 81 | Wirelessco | 86 |
| Charlotte | AT&T | 67 | BellSouth | 71 |
| Dallas | Primeco | 88 | Wirelessco | 88 |
| Boston | AT&T | 122 | Wirelessco | 127 |
| Philadelphia | AT&T | 81 | Phillieco | 85 |
| Washington | ª | | AT&T | 212 |
| Total revenue: | $7.7 billion (including pioneer preference awards) | | | |

ªPioneer preference award.

*Notes:* Wirelessco includes Sprint, TCI, Comcast and Cox. Primeco includes Bell Atlantic, US West, AirTouch and Nynex.

*Source:* FCC.

efficient allocation; that is, assigned the licenses to the firms best able to use them, given the complementarities among licenses and the gains from aggregation.

Only time will tell whether the auctions put the licenses into the hands of the right firms. The secondary market will give some evidence. A large number of licenses being resold would suggest that the auction had produced an inefficient allocation. Little secondary-market activity would not provide decisive evidence of efficiency, however, because the secondary market will be thin, with few players and large informational asymmetries, and cannot be expected to work smoothly. Conclusive evidence on the efficiency of the auction outcome will come only after the firms have their mobile-communications services operating, which will take several years. The bid data do, however, allow us to speculate on whether the simultaneous ascending auction allowed the bidders to construct efficient license aggregations.

For the regional narrowband auction, the FCC divided the country into five regions, with six licenses in each. Four bidders—Pagemart, PCS Development Corp., Mobilemedia, Inc., and American Wireless Messaging—assembled nation-wide licenses, winning all five licenses in a particular wavelength. Also, two bidders built consistent subnational aggregations: AirTouch won three of the licenses on one waveband, and Lisa-Gaye Shearing won three on another (see Table 2). This suggests that the auction did enable the bidders to build their desired aggregations.

Did the bidders in the broadband MTA auction achieve efficient aggregations? PacTel won the aggregation that it had made no secret it was seeking: northern plus southern California. The other three big bidders appeared to bid for the li-

censes that filled gaps in their cellular holdings.[8] They did not fill all of their gaps, but they came close. Of the 46 contiguous-U.S. licenses, when previous cellular holdings are added to the new PCS winnings, AT&T owns 40, Wirelessco owns 39 and Primeco owns 38. Each of these firms holds cellular or PCS licenses in each of the top ten markets (with the exception of Wirelessco's missing Chicago, since all three competed for the two Chicago licenses).

The bid data suggest, then, that the auctions facilitated license aggregation. The bidders agreed. After the broadband auction, Primeco president George F. Schmitt said his group expected to have a complete nationwide network operating within two years. Steven Hooper, chairman of AT&T's mobile-telephone subsidiary, said, "This enables us to build a nationwide network."[9]

A failure some feared for the auction appears not to have occurred. A bidder seeking a particular aggregation might unexpectedly fail to win a crucial license. Then the licenses that bidder wins might be worth less than their total price, bid in anticipation of winning the lost license. Some economists argued that, for this reason, bidders should be allowed to bid for combinations of licenses, rather than bidding license by license.[10] It does not appear, however, that bidders became exposed in this way. If they had, we would expect to see them withdrawing bids. In fact there were few withdrawals, and those that occurred did not seem to result from license aggregation failures. In the broadband MTA auction, for example, Wirelessco seemed not to change its bidding behavior after it lost the Chicago licenses. Failure to complete an aggregation might not be serious. The complementarities may not be so sizable as to generate large discontinuities in the values of aggregations. Also, substitution is possible: Wirelessco could complete its set by winning licenses in a later auction, or by forming alliances with other firms.

Congress stated a further criterion for the auction, beyond efficiency and revenue. Some licenses should go to minority- and woman-owned firms, small businesses and rural telephone companies. The initial auction design had ambitious provisions to aid these so-called "designated entities." FCC chairman Reed E. Hundt said this would be "the single most important economic opportunity made available to women and minorities in our country's history." The first two auctions ran under these rules. Then a June 1995 Supreme Court judgment that an affirmative-action program must be "narrowly tailored" to support "a compelling

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[8] Marketing and brand-name gains come from offering nationwide mobile services. Cellular and PCS are not perfect substitutes, however, as telephones that transmit on both spectrum bands are expected to be more expensive than those specialized to a single band. The FCC's antimonopoly rules prevented a bidder from acquiring a broadband license in a region where it already held a cellular license.

[9] Reactions from a story in the *Wall Street Journal*, March 14, 1995, p. A12.

[10] Combinational bidding has some problems. Because of the huge number of license aggregations, combinational bids create impossibly complex computations. The FCC could prespecify a limited number of aggregations. But the existing theory of combinational bidding (Bernheim and Whinston, 1986; Banks, Ledyard and Porter, 1989; Branco, 1995; Rothkopf, Pekec and Harstad, 1995) offers little guidance on the effects of combinational bidding with restricted permissible aggregations. Experiments often find gains from combinational bidding; but the theory currently does not say when restricted combinational bidding would work better, for either revenue or efficiency, than the much simpler single-license bidding.

governmental interest'' induced the FCC to scrap the race- and gender-based preferences. Some preferences remain, however. The fourth auction, offering 30 mHz (not held at the time of writing), is to be limited to entrepreneurs (defined as firms with less than $125 million in annual revenue and $500 million in assets) and small businesses (revenue under $40 million), with the latter receiving bid discounts.

The designated entities were eligible for a discount in the nationwide narrowband auction: if they won they would pay 25 percent less than their bid. The size of this discount was set by guesswork as, this being the first auction, there were no data from which to estimate its effects. As it turned out, 25 percent was too small for any of them to win licenses. For the second auction, the regional narrowband auction, the FCC used higher preferences. On two of the six wavebands the designated firms were offered a 40 percent discount. Minority bidders won all 10 licenses on which they were offered discounts (see Table 2). PCS Development Corp., a start-up minority company, won a nationwide aggregation. The prices on the designated licenses were bid so much higher than the other licenses that in net terms, after subtracting the discount, the designated firms paid approximately as much as the nonfavored firms. (The designated entities still received some special treatment, however, as they were permitted to pay in installments.)

Bid discounts not only address the policy goal of getting licenses into the hands of the designated firms, but also can actually boost the government's revenue (Myerson, 1981; McAfee and McMillan, 1988, 1989). The designated bidders, presumably, have a lower willingness to pay for the licenses than the nondesignated firms— otherwise preferences would not be needed. With level-playing-field bidding, they would therefore not be competitive with the nondesignated firms, who could bid low. A discount for the designated firms stimulates the bidding competition, forcing the nondesignated firms to bid higher. This may have happened in the narrowband auctions. Prices rose 12 percent higher in the regional auction than in the nationwide auction (the average price per mHz-pop was $3.10 in the nationwide auction and $3.47 net of discounts in the regional auction). Perhaps, as the theory says, the discounts did increase the bidding competition.

## Bidder Strategies

"Bidding for the PCS licenses is like playing a dozen hands of billion-dollar poker at once," said the *Wall Street Journal.*[11] Bidder strategies can be aggressive or passive. The theorists, when designing the auction, expected that the bidders would be cagey, revealing to their rivals as little of their intentions as the auction rules permitted. As it happened, in the first two auctions many of the bidders behaved much more aggressively than this. But in the third, the broadband MTA auction,

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[11] Story on February 23, 1995, p. B1.

the huge amounts of money at stake induced the bidders to be circumspect, as the theorists had predicted.

Aggressive bidding took the form of "jump bidding": entering bids that were far above the required minimum. In the nationwide narrowband auction, one spectacular jump bid was 138 percent above the previous high bid. In nine instances, bids were between 40 and 70 percent above the previous high, and in 20 cases they were 20 to 40 percent higher (minimum increments were typically 5 to 10 percent). The jump bidding occurred in the early rounds, including the opening bids. The 30 bids that beat the standing bid by 20 percent or more all came in the first 27 rounds of the auction (which took 46 rounds to close). An extreme form of jump bidding, which happened on several occasions, involved submitting a higher bid for a license on which the bidder already had the standing high bid. Jump bidding was common also in the regional narrowband auction.

Jump bidding is intended to signal the jump bidder's toughness, to try to persuade the others it is pointless to compete (Avery, 1993). Did jump bidding achieve the bidders' aims, or did it just aid the FCC by speeding up the auction? Despite jump bidding's prevalence in the two narrowband auctions, most of the jump bids were eventually overtaken. Few of the final prices were reached by a jump bid; instead, the final prices were reached gradually, by a series of minimum-increment bids. This suggests that the jump bids had little effect, for they did not deter competitors.

By the time of the third and biggest of the auctions, the broadband MTA auction, the bidders, having observed the two narrowband auctions, had apparently decided that jump bids did not work, for they mostly eschewed them. A few jump bids were used. Sometimes a bid beat the standing bid by twice the minimum increment; in round 30 ALAACR Communications, Inc., raised Pacific Telesis's $183 million bid on Los Angeles to $300 million; in round 81 Wirelessco submitted bids on four small markets that exceeded the standing bids by 10 times the minimum increment; and on a handful of occasions bidders such as SouthWest Bell and ALAACR raised their own standing bid. But most bids beat the standing bid by just the minimum increment or slightly more.

The broadband bidders bid cautiously in another way, by not bidding for more licenses than the activity rule required. The auction's pace was driven by the auction rules more than by the bidders' decisions. Total revenue rose at the rate set by the mechanism. The effect of the three stages of the activity rule is seen in Figure 1.[12] In each stage, bid activity steadily dropped off, until the imposition of the next stage (in rounds 12 and 65), with its stricter activity requirements, caused a jump in bid activity. The revenue curve is scallop shaped, steepening when a new stage starts and roughly concave within each stage.

The broadband MTA auction had few bidders relative to the number of licenses on offer. The low excess demand, just two-to-one, gave rise to fears that the bidders might collude. A drawback of the simultaneous ascending auction is that

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[12] This figure was devised by Peter Cramton for the FCC.

*Figure 1*
**Revenue and Bidding Activity, MTA Broadband PCS Auction**
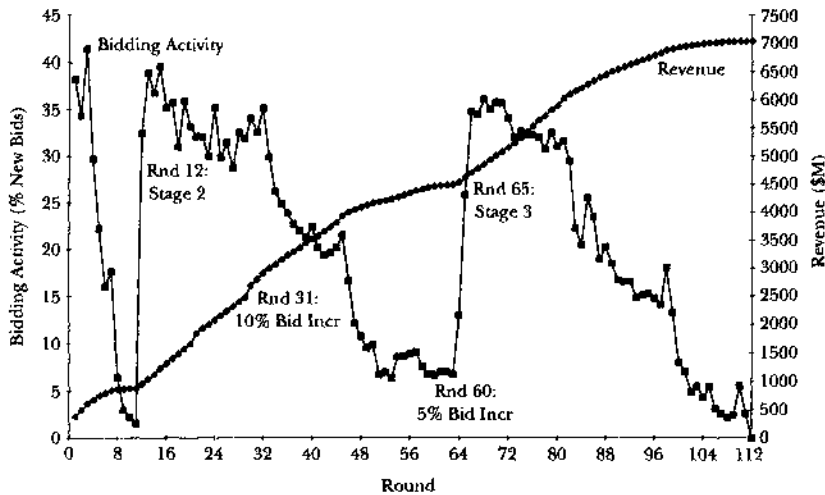


collusion is easier than under a single round of sealed bids. Through their bidding patterns in the early rounds, the bidders might in effect say to each other: "This is 'my' territory. Stay away from it, and I will stay away from 'yours.' If you ever bid on it, I will drive up the price of 'yours' in retaliation." The FCC could have hindered collusion by revealing only the bid amounts between rounds, and not the bidders' identities. It chose not to do this in the broadband auction and instead gave out full details of each round's bidding, because it judged that the risk of collusion was outweighed by benefits of the information. (Bidder identities are useful to the bidders for evaluating the meaning of others' bids, reducing the winner's curse and generally assisting sensible bidding.) Some of the firms may have tried to coordinate their bids. Primeco president George F. Schmitt was reported as saying during the broadband MTA auction: "You mess with me in Chicago, you pay."[13] Primeco won its Chicago license, however, only after a bruising three-way battle for the two licenses, involving Primeco, Wirelessco and AT&T, which drove the bids to the highest level in the nation. Schmitt's threat, if such it was, had little effect. It takes only one maverick bidder to upset an attempt at collusion. ALAACR, in particular, seems to have used a strategy of bidding on any major license that was relatively underpriced (and American Portable Telecommunications seems to have bid similarly); and this helped to keep the bidding competitive.[14]

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[13] The Schmitt quotation is from the *New York Times*, March 27, 1995, p. C9.
[14] ALAACR is owned by Craig McCaw, who became a billionaire by building America's leading cellular company and then, after selling it to AT&T, bid on his own account for the PCS licenses. Despite its aggressive bidding, ALAACR ended up without a single license. However, according to *Forbes* (July 3,

One of the reasons for adopting the simultaneous ascending auction was to aid efficient license aggregation by allowing a bidder to switch to a back-up aggregation if the bid prices in its first-choice aggregation rose too high. The bid data contain many examples of back-up strategies. In the nationwide narrowband auction, Nationwide Wireless Network began by bidding for two of the 62.5 kHz licenses. In round 26, about the halfway point, it apparently decided that the prices were too high, and it switched to bidding for a single 100 kHz license, which is what it won. In the regional narrowband auction, AirTouch began by apparently seeking a nationwide aggregation of five licenses. Then it scaled back, and sought and won three licenses, supplementing the nationwide license it had won in the first auction. During the broadband MTA auction, firms such as GTE and Wirelessco often shifted their bidding across different license sets.

A consistent pattern of closing (especially in the narrowband auctions, but less clearly in the broadband MTA auction) was that, as equilibrium came near, the winning bidders tended to be established first on the highest-valued licenses. Then the activity shifted progressively to lower-valued licenses, with the lowest-valued settling last.

## New Theory of Multiunit Auctions

The spectrum sale is more complicated than anything in auction theory. No theorem exists—or can be expected to develop—that specifies the optimal auction form. The auction designers based their thinking on a range of models, each of which captures a part of the issue. The basic ideas used in designing the auction and in advising the firms on bidding strategy include the way the different bidders' valuations are related—they are partly idiosyncratic and partly common, or *affiliated*—and the effects of this on bidder behavior (Milgrom and Weber, 1982); how auctions reveal and aggregate dispersed information (Wilson, 1977); and the logic of bidding in the face of the winner's curse (Wilson, 1969; Milgrom and Weber, 1982). Other ideas used include the revenue-increasing effect of bid discounts (Myerson, 1981; McAfee and McMillan, 1988, 1989) and reserve prices as substitutes for bidding competition (Myerson, 1981; Riley and Samuelson, 1981).[15]

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1995, p. 64), "McCaw had a grand time giving ulcers to the functionaries at the big bidders and adding hundreds of millions to the U.S. Treasury. 'Craig McCaw thought he was playing Nintendo. He was having the time of his life,' says Sam Ginn, chief executive of AirTouch." Incidentally, McCaw envisages novel uses of the spectrum: according to *Fortune* (December 12, 1994, p. 102), he "once suggested in all apparent seriousness—as color drained from the face of a PR man in attendance—that the FCC should reserve spectrum for telepathic communications to be made possible by brain implants he thinks will exist some day."

[15] There is a direct link between game theory's Nobel laureates and the spectrum auction. The ideas with which Nash, Harsanyi and Selten are associated—Nash, Bayesian and perfect equilibrium—are the basic tools of the theory used in designing the auction.

A lesson from this experience of theorists in policymaking is that the real value of the theory is in developing intuition. The role of theory, in any policy application, is to show how people behave in various circumstances, and to identify the tradeoffs involved in altering those circumstances. What the theorists found to be the most useful in designing the auction and advising the bidders was not complicated models that try to capture a lot of reality at the cost of relying on special functional forms. Such theorizing fails to develop intuition, as it confounds the effects of the functional forms with the essential elements of the model. Instead, a focused model that isolates a particular effect and assumes few or no special functional forms is more helpful in building understanding.

The spectrum auction, itself based on theory, has in turn sparked a new wave of theorizing. Although sequential auctions and single-round simultaneous auctions had been modeled, there had been little formal work on simultaneous ascending auctions of the sort the FCC used. Most of the existing theory omitted the crucial feature of the spectrum auction: the fact that the licenses complement and substitute for each other. Prompted by the FCC auctions, theorists are beginning to address this issue, though because of the intrinsic difficulty of the question, the existing attempts are preliminary.

One promising approach is to assume away asymmetries of information and the strategic behavior they induce, in order to focus on how bidding proceeds when the goods complement and substitute for each other. Complementarities mean market-clearing prices may not exist. Equilibrium is likely to exist if the buyers have similar views about how the goods should be aggregated, whereas it may not if they disagree about what constitutes good aggregations.[16] Some recent research has identified conditions for the existence of equilibrium in this sort of auction. Gul and Stacchetti (1995a,b), for example, show that a certain kind of substitutability among goods ensures existence. Their model also yields a decentralized price-setting process in which prices rise when demand exceeds supply.

Strategic behavior in a simultaneous ascending auction is analyzed by Menezes (1995), again assuming complete information. Prices are quoted and rise until excess demand becomes zero. The bidders' game playing means there are many equilibria. On applying a natural way of selecting one of the equilibria—the iterated elimination of weakly dominated strategies—Menezes shows, remarkably, that the sale takes place at the opening prices. Bidders forecast how much they will eventually purchase and shrink the amounts they demand in the first round to this level; the consequence of iterating this logic is immediate sale. This result rests on the

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[16] An example with no equilibrium has two items and two buyers. Buyer 1 sees the two goods as perfect substitutes, but buyer 2 sees them as perfect complements. Buyer 1 puts a value of 2 on getting either good 1 or good 2 or both. Buyer 2 puts zero value on having either good alone, but puts a value of 3 on having both. The allocation that is efficient, and therefore the only candidate for a Walrasian equilibrium, gives buyer 2 both goods, for a value of 3. Since buyer 1 gets nothing, the price of each good must be 2, for otherwise buyer 1 would buy one of them. But buyer 2 will not buy the goods at those prices. (If buyer 2 were allowed to bid all-or-nothing for the aggregation, however, the efficient outcome would result.) For more on existence, see Bikhchandani and Mamer (1994).

unrealistic assumption of complete information; but it provides a warning about the peculiar possibilities in simultaneous ascending auctions.[17]

More new theory is needed. Features of the FCC's auction should be modeled. How should the activity rule parameters be set? How do the bid withdrawal rules affect the bidding? If bidders fear being stuck holding an incomplete bundle by losing a crucial license, do they bid unduly cautiously? Is this caution lessened by the availability of substitute licenses? How does the FCC-style auction, with its single-license bidding, compare in efficiency and revenue with combinational bidding under certain prespecified permissible combinations? Together with experiments (Plott, 1994), theory will map the scope and the limits of the simultaneous ascending auction.

## Other Uses of the Simultaneous Ascending Auction

Auctions are used when the seller does not know the bidders' willingness to pay for idiosyncratic items for which there is no well-functioning market. The fundamental purpose of any auction is to reveal the bidders' valuations, thereby extracting a good price for the seller. The simultaneous ascending auction extends this notion of value-discovery to multiple items and how they fit together. The seller need not know how the items for sale complement or substitute for each other, as the auction induces the bidders to express their ideas about serviceable aggregations, and so the market process determines the outcome.

The evidence from the FCC auctions is that the simultaneous ascending auction is an effective mechanism for selling interdependent items. The simultaneous ascending auction has many other potential uses for selling multiple items that are complements or substitutes. Further possible public-sector uses include the sale of oil and mineral rights, timber and grazing rights, houses held by the Resolution Trust Corp. or the Federal Deposit Insurance Corp., and airport landing rights. The FCC might also begin selling spectrum rights to broadcasters, who currently receive a huge hidden subsidy through receiving spectrum for free. In the private sector, the simultaneous ascending auction could be used for art and real estate.

More innovative uses might also emerge. One possible use is by a firm buying inputs from other firms. Conventional procurement specifies the level of assembly at which components are to be purchased. If instead a simultaneous mechanism were used, the procuring firm could define the components finely and have the

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[17] Krishna and Rosenthal (1995) model a simultaneous auction with bidders who are either local bidders, who want only one of the items, or global bidders, who get extra value if they acquire both, and show the global bidders' strategies may be discontinuous. Rosenthal and Wang (1995) extend this to a common-value case. In Jehiel, Moldovanu and Stacchetti (1995), one bidder's ownership has externalities for the others (for example, MCI may prefer GTE to obtain a license rather than AT&T). The negative externalities mean a bidder may pay even when the item is not sold, and the item may fail to sell even though a bidder is willing to pay more than the seller's value. Jehiel and Moldovanu (1995) add an after-market to the auction, finding that after-market trading does not ensure efficiency.

potential suppliers bid component by component, with the possibility of winning several contracts and so supplying a bundle of components. By the set of components it bid for, each supplier would reveal its economies of scope. Another possible application is in the sale of a multidivisional corporation. The simultaneous auction could allow buyers to bid division by division. The bidders could thereby express their ideas on which parts of the firm fit together and which should be spun off. The uses of this new auction have just begun.

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