

Chapter 1: Auctioning the Radio Spectrum

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"Now we're using the auctions to put licenses in the hands of those who value them the most." - Albert Gore

On December 5, 1994, United States Vice President Albert Gore banged the opening gavel on what the government hailed as "the largest auction of public assets in American history."¹ The auction, conducted using a design created by economic theorists, was watched closely by the press. When the auction closed on March 12, 1995 with the high bids totalling over \$7 billion, a *New York Times* columnist declared it to be "the greatest auction in history."² The size of the auction, the novelty of its rules, the media hype surrounding it and the its potential application to government privatization programs has subjected the auction to scrutiny by scholars and policymakers around the world, who hope to learn what economic theory and theorists can contribute to the very practical business of auction design.

The December auction was the fourth in a series conducted by the U.S. Federal Communications Commission (FCC). All four were sales of licenses to use portions of the radio spectrum that could be used for delivery of a new generation of wireless communications services, called "*personal communications services*" (PCS). Two of the previous auctions had employed the same rules in massive sales of spectrum for use in paging services. What most distinguished the December auction was the number of licenses sold and their unusual value. PCS customers will use wireless devices for communication: telephones, data communications devices, fax machines, two-way

¹Fifth Report and Order in PC Docket No. 93-253, paragraph 1.

²William Safire, "The Greatest Auction Ever," *New York Times*, March 16, 1995, page A17.

voice pagers, inter-active home videos for services like teleshopping, etc. The large and growing demand for these services makes licenses to the spectrum necessary to deliver them worth many billions of dollars.

To many economists, the most important breakthrough in the spectrum auctions was the fact that auctions were used at all. Auctioning is the third system the FCC has used to assign spectrum licenses. At first, licenses were assigned by regulators to the companies they believed would put the spectrum to its best use. But the hearing process the administrators used was burdened with time-consuming due process requirements and subjected to intense political pressures. The system failed to respond quickly to changing market and technical conditions. The process was changed in 1982, when licenses to spectrum for use by cellular telephones were assigned randomly among applicants by lottery. Winners were free to resell their licenses. The new process did speed up license assignments. However, it also rewarded speculators with multimillion dollar prizes. It wasted other resources as well: probably more than a million hours of professional time were spent preparing incorporation documents and license applications for bidders who had no intention of operating an actual telephone business. In addition, the need to buy licenses from the auction winners generated costs for the telephone companies but no revenues for the public that supplied the spectrum. It may also have contributed to the geographic fragmentation of the cellular industry, delaying the introduction of mobile telephone services that would work wherever the consumer traveled in the United States.

A better process was needed. For over forty years, economists had argued that auctions were such a process,³ but the argument had been largely theoretical. The question of exactly how an auction market for radio spectrum should be designed and implemented was hardly broached.

A small cadre of economists with backgrounds in game theory knew that not just any auction design would do. There can be huge differences in the assignments and revenues that result from different auction rules. Both economic theory and laboratory experiments concluded that the most obvious procedure – auctioning the licenses one by one in sequence – would be unlikely to meet the government's stated objective of putting licenses into the hands of those who value them the most. The decision to use an auction at all was a policy breakthrough, but getting the auction design right was also critically important for the new policy's success.

Most non-economists would be surprised to learn how little most professional economists know about the details of how auction markets or, indeed, any kind of markets, are run. In introductory economics courses, economics is typically represented as consisting primarily of the study of market outcomes and its roots in individual and firm behavior. The leading elementary textbooks teach about the effects of taxes, rent-controls and other forms of government regulation on individual choices, prices, quantities sold, and the efficiency of market outcomes, but all this is done without ever specifying exactly who sets the market prices, or how. Yet in a complicated problem like the assignment of PCS licenses, the detailed rules of the market do matter. For assessing alternative

³The idea of auctioning spectrum rights can be traced back to a pair of papers: Leo Herzel (1951), "'Public Interest' and the Market in Color Television Regulation," *University of Chicago Law Review* 18: 802-816, and Ronald Coase (1959), "The Federal Communications Commission," *Journal of Law and Economics* 2: 1-40.

auction rules, game theory – with its emphasis on the relations between rules, behavior and outcomes – plays a unique and valuable role.

To illustrate just how much the rules of an auction can matter, let us digress to review the outcomes of other auctions. Of particular interest are the spectrum auctions conducted in New Zealand and Australia in the years and months just before the regulators were called upon to choose rules for the U.S. spectrum auctions.

Spectrum Auctions in New Zealand and Australia

An auction is a game with specific, well defined rules. The rules cannot be evaluated individually. Rather, one must think about how all the rules, in combination, affect the bidders' behavior. That requires thinking through the strategic options that the rules allow, the payoffs for bidders associated with the various options, and the bidders' expectations about how their competitors might play. These are the basic elements of a game theoretic analysis. Because they failed to conduct such an analysis, the governments of New Zealand and Australia had little warning of the consequences of the rules they adopted.

New Zealand conducted its first auctions of rights to use radio spectrum in 1990. Some of the rights took the traditional form of “*license rights*” to use the spectrum to provide a specific service, such as the right to broadcast television signals using those frequencies. Others consisted of “*management rights*” according to which the buyer may decide how to use the spectrum, choosing, for example, between television, wireless telephones, paging, or some other service. When management rights are sold, private interests have an incentive to allocate spectrum to its most profitable uses. In the United States, only license rights have so far been offered for sale.

Acting on the advice of the U.S.-U.K. economic consulting firm National Economic Research Associates (NERA), the New Zealand government adopted a *second price sealed-tender auction* for its first four auction sales. According to William Vickrey's (1961) original description of the second price auction, its rules are these: Each bidder submits a sealed tender and the license is awarded to the highest bidder for a price equal to the *second* highest bid or the minimum price, if that is larger. The auction gets its name from the fact that it is the second highest bid that determines the price.

The very idea of a second-price sealed-tender auction strikes many people as strange, but the auction rules have a solid theoretical grounding when applied in the proper context. By using a sealed tender format, the auction avoids the requirement that all the bidders be physically present at the same time and presents each bidder with an easy bidding problem. Also, provided that bidders behave rationally, this second-price rules can duplicate the outcome of the standard English auction.

To understand this theory, we first need to characterize the outcome of traditional English auctions such as the ones conducted by the leading auction houses. Suppose that the bidders in the auction are rational and plan ahead. Then, before the auction, each would determine in advance how high to bid – an amount that we may call the bidder's *reservation price*. During the auction, the auctioneer asks for higher and higher prices until no bidder is willing to bid any higher. Now consider the behavior of the last bidder to drop out of the bidding. That bidder's final bid before it dropped out was no more than its reservation price and the next required bid exceeded its reservation price. The final price lies between these two numbers. So, if the minimum bid increments are not too large, the final price is approximately the last losing bidder's reservation price. Since a self-interested bidder who values the license at X will set a reservation price of X in the auction, the winner in the ascending bid

auction is the bidder with the highest valuation and the price is (approximately) equal to the second highest valuation.

Because the strategies executed by rational bidders in such an auction are so simple, we can imagine that a busy bidder would happily delegate the bidding to a competent agent in order to avoid the need to be physically present at the auction. A bidder could instruct the agent as follows: "Go to the auction and bid steadily on my behalf for this one good in which I am interested. Pay any price up to X, but do not pay more." If that happened, the agent with the highest reservation price would acquire the item for a price (approximately) equal to the second highest reservation price. With just one item for sale, there is no need for each bidder to hire a separate agent. Instead, each bidder could simply write its reservation price on a slip of paper and have the auctioneer serve as every bidder's agent. Executing the instructions, the auctioneer would award the item to the highest bidder for a price equal to the second highest written bid. Conducted this way, the ascending bid auction is effectively converted to a sealed-tender auction with the price set by second-price auction rules.

As compared to most other kinds of auctions, the advantages of the second-price auction are two. First, it duplicates the outcome of the ascending bid auction without any need to assemble the bidders together or to have them hire separate agents. Second, it presents each bidder with a simple strategic bidding problem: each merely has to determine its reservation price and bid it. There is no need to make estimates of the number of other bidders or their values, since those have no bearing on a rational bidder's optimal bid.

The analogy between English and second-price auctions can also be exploited when there are sales of multiple identical items. For example, if an auction rule specifies that the five items for sale are to be awarded to the five highest bidders in a single ascending bid competition then the expected

outcome is that the five items will be to the five bidders with the highest values for prices approximately equal to the sixth highest reservation price among the bidders. To duplicate that with a sealed-tender auction, the rule must award items to the five highest bids for a uniform price equal to the highest rejected bid. A similar uniform-price rule has sometimes been used in the sale of U.S. Treasury bills⁴ and seems to have worked well.

The New Zealand government, on the advice of its consultants, did not adopt this theoretically appropriate extension of the second-price auction. Instead, it chose to conduct a separate second-price sealed-tender auction for each license. Moreover, it required the sealed-tenders for similar licenses to be submitted simultaneously.

To anyone who has studied game theory, it is obvious that this set of rules results in an auction that is quite different from the theoretical extension of the second-price rule described above. It results in a different set of strategies for the bidders and destroys the close theoretical connection between second-price sealed-bid auctions and ascending-bid auctions. Standard game theoretic analysis predicts that the performance of the New Zealand rules will be quite bad.

The most obvious problem with the New Zealand rules is that the bidding problem is no longer a simple and straightforward affair. Each bidder must now decide which licenses to bid on. Even a bidder that wished to acquire only a single license might nevertheless find it better to place relatively low bids for several licenses rather than placing a single relatively high bid for just one license. These extra bids are a form of insurance: if its high bid loses, its low bid on some other license may still win. On the other hand, if it bids for several licenses, it may win several licenses, paying more than it has budgeted for licenses it doesn't need. What should a bidder do? To decide, it must attempt to predict

⁴The Treasury rule set a uniform price equal to the lowest accepted bid.

what its competitors will do. This pattern of reasoning confirms that the strategic problem is much more intricate than in the standard second-price auction.

In the next chapter, we will return to make a game theoretic analysis of the New Zealand rules. Our analysis will show that even in the most favorable circumstances, the New Zealand auction rules could not be expected to assign licenses "to those who value them the most." Randomness and inefficiency are likely to plague the auction outcome. It is especially ironic that the very simultaneity that is theoretically so damaging to the performance of sealed-tender auctions is, according to the theory, a critical ingredient for success when the individual auctions are conducted in an ascending bid format, as in the US PCS auction.

So much for theory. The actual outcome of the first New Zealand auction is shown in Table 1. As the table shows, one bidder, Sky Network TV, consistently bid and paid much more for its licenses than most other bidders. Totalisator Agency Board, which bid NZ\$401,000 for each of five licenses, acquired just one license at a price of NZ\$100,000, while BCL, which bid NZ\$255,000 for just one license, paid NZ\$200,000 for it. Without knowing the exact values of various numbers of licenses to the bidders, it is impossible to be certain that the resulting license assignment is inefficient, but the outcome certainly confirms that the bidders could not guess one another's behavior. If Sky Network, BCL, or United Christian had been able to guess the pattern of prices, they would have changed the licenses on which they had bid. The empirical data also show little connection between the demands expressed by the bidders, the numbers of licenses they acquired, and the prices they eventually paid. That creates a presumption that the outcome was economically inefficient. The results of the second, third and fourth New Zealand auctions similarly indicated randomness and inefficiency.

Table 1

Winning Bidders on Nationwide UHF Lots 8 MHz License Rights			
Lot	Winning Bidder	High Bid (NZ\$)	Second Bid (NZ\$)
1	Sky Network TV	2,371,000	401,000
2	Sky Network TV	2,273,000	401,000
3	Sky Network TV	2,273,000	401,000
4	BCL	255,124	200,000
5	Sky Network TV	1,121,000	401,000
6	Totalisator Agency Board	401,000	100,000
7	United Christian Broadcast	685,200	401,000

Source: Tom Hazlett, "A Brief History of Spectrum Auctions," unpublished notes, November 1994.

A second problem was even more embarrassing to New Zealand's government officials. John McMillan (1994) described it as follows: "In one extreme case, a firm that bid NZ\$100,000 paid the second-highest bid of NZ\$6. In another the high bid was NZ\$7 million and the second bid was NZ\$5,000." Total revenue, which consultants had projected to be NZ\$250 million, was actually just NZ\$36 million. The second-price rules allowed public observers to get a good estimate of the winning bidders' profits, some of which were many times higher than the price. To avoid further embarrassment, the government shifted from the second-price sealed tender format to a first-price sealed-tender format, in which the highest bidder pays the amount of its own bid.. As our analysis in the next chapter will show, that doesn't necessarily result in higher prices. It does, however, conceal the bidders' profits from a curious public.

The change in auction format did not solve the most serious auction design problems. A first-price auction with several licenses for sale still forces bidders to choose between the risk of being shut out of licenses and the risk of acquiring too many licenses. The revised design is still a guessing game in which luck plays a big role. Allocations are random, and the licenses are too rarely assigned to the bidders who value them the most.

One might wonder whether the failure of the New Zealand auction to assign licenses to those who value them most is a serious problem. After all, the bidders are permitted to buy and sell licenses after the auction. Trade of that sort could help correct the auction misallocation. Bargaining among the bidders, however, is a difficult matter both in theory and in practice. The relevant theory will be reviewed in the next chapter. An illustration of the difficulty of such bargaining in practice is the inefficient assignment of cellular telephone licenses in the United States. Consumers' demonstrated willingness to pay large sums for the "roaming" services suggest that there are important economies in establishing cellular systems with wide geographic coverage. Nevertheless, such systems have emerged only slowly, which testifies to the difficulty of using contracts or resale to correct an initial misallocation of spectrum rights.

In 1993, it was Australia's turn to conduct spectrum auctions. Determined not to repeat the New Zealand debacle, they decided to stick with the "tried-and-true" method of the first-price auction. Though this is a standard method of sealed tenders, there are still many details to be decided. Should licenses be sold simultaneously or in sequence? Should there be a bid submission fee? Should deposits be required? Should a single bidder be allowed to submit multiple bids? What should happen if a bidder defaults on its bid? In the actual auction, there were no deposits required, no restriction against multiple bids, and no default penalty. The rules prescribed that if a bidder fails to pay its bid amount within a

specified period, then the license is awarded to the maker of the second highest bid, who again is permitted a period of time to make its payment. This process continues until some bidder is willing to pay the amount of its bid.

In April of 1993, two newly formed companies surprised the established players by placing unexpectedly high bids of A\$212 million and A\$177 million for two satellite television licenses. One of the bidders had paid-in capital of just A\$100. When the requisite time period had elapsed and neither bidder had paid, the government rejected those bids and announced the second highest bids, which were submitted *by the very same bidders* who had submitted the high bids. Under the rules, this was perfectly legal. The bidders were again allowed a period to find the necessary funding before those bids, too, were rejected. This pattern of default, rejection, and announcement of the new winning bid continued for ten months. While the license assignment was delayed, the bidders negotiated with potential buyers. The first license was eventually bought by the defaulting bidder for just A\$117 and immediately resold for a A\$21 million profit. The second was acquired for A\$77 million and resold for an unknown price, but presumably at a profit.

With this background still fresh in the minds of the regulators, the United States embarked on its auction adventure in the early Fall of 1993.

The U.S. Decision About Auction Rules

From 1927 until 1982, radio spectrum licenses in the United States were assigned by a process known as "comparative hearings," in which a federal agency would evaluate competing proposals to use a band of the available spectrum and decide which best served the public interest. By 1982, the need to issue thousands of new cellular telephone licenses had begun to overwhelm the U.S. Federal

Communication Commission's capacity to conduct comparative hearings. Long delays in the license assignments threatened to make the United States a backwater in wireless communications. The Republican president proposed that a system of auctions be adopted to replace the system of comparative hearings. However, with support from a telephone industry hoping to continue to get valuable licenses free of charge, Congress authorized the FCC to assign the licenses by lotteries instead. Participation in the lotteries would be open to any telephone company, regardless of its experience or qualifications. According to advocates of this plan, a secondary market in licenses could be counted on to sort out who should own which license. The important thing was to make license rights transferable and assign them to somebody.

The upshot of this plan was the creation of a new business for Washington law firms: organizing "telephone companies" for the sole purpose of filing lottery applications to acquire valuable cellular telephone licenses. During the lottery era, more than four hundred thousand applications were filed.⁵ Most lottery winners resold their rights at large profits to older telephone companies. In one case, a "telephone company" that had won the right to supply cellular services to Cape Cod promptly resold their license to Southwestern Bell Telephone Company for \$41 million.⁶

With estimates of the value of the spectrum given away in the tens of billions of dollars and with mounting political pressures to do something about the huge U.S. federal budget deficits, Congress decided to put an end to what the legislation called the "unjust enrichment" of lottery winners. The Omnibus Budget Reconciliation Act passed in July of 1993 authorized the FCC to

⁵John McMillan, "Why Auction the Spectrum?" *Telecommunications Policy*, Vol.19, No. 3, pp. 191-199, 1995.

⁶Ibid.

conduct auctions for rights to use the airwaves and mandated that it begin assigning licenses within just ten months. The license selling price, this time, was to accrue to the U.S. Treasury, rather than to some randomly determined lottery winner.

With billions of dollars at stake, thousands of licenses to be auctioned, and the need for public hearings and comment before the auction rules could be determined, ten months would be a short timetable to conduct even a routine auction. The spectrum auctions, however, were not destined to be routine, and the amount of effort devoted to the auction design by economists outside the FCC was quite unexpected.

In establishing the auction rules, the FCC had much to decide. First was the criterion by which alternative auction rules were to be evaluated. According to the auction legislation, the primary objective of the process was to ensure the “efficient and intensive use” of the spectrum. These words were interpreted as a mandate to put spectrum licenses in the hands of those who value them the most.⁷

With this criterion in mind, a series of economic theorists paraded proposals before the FCC's Office of Plans and Policy (OPP), which was to recommend a design to the Commissioners. Two of the proposals – one submitted by the National Telecommunications and Information Administration and one by Pacific Bell – advocated new designs that would require computers to be run successfully. The first reaction to these proposals was one of extreme skepticism. Robert Pepper, head of the OPP, objected that the proposals would make the FCC a beta test site for a new design and new software. With billions of dollars at stake, the risks seemed too high. The skepticism was not limited to FCC

⁷According to economic theory, this criterion is most appropriate when the markets are “*perfectly competitive*,” that is, when the parties have no ability to affect prices, which is not the case in this situation. The criterion may also be appropriate when the parties are expected to profit equally from providing service, so that the difference in license values reflects only or primarily a difference in the firm's ability to deliver valuable services to consumers.

staff. *The Economist* magazine, commenting on the influence of mathematical economists and game theorists on the FCC's decision process, described it as letting "[t]he lunatics take over."⁸ However, the enabling legislation had explicitly called for experimentation with auction formats and the economic theorists had made a strong case that traditional designs were seriously inadequate for this auction problem. So, despite its reservations, the OPP staff recommended the experiment and the FCC decided to become the beta test site for a brand new auction design.

Why were traditional auction designs inadequate? Why was a more complicated design desirable? Dependencies among the licenses themselves dictated the complexity. There were thousands of PCS licenses to be assigned. Some licenses, such as ones to use similar spectrum bands to provide a given service, were nearly perfect substitutes for one another. Others, such as licenses to provide the same service to different regions of the country in the same spectrum band, were complements. To permit an efficient license assignment, an auction must allow bidders to consider various packages of licenses, combining complements and switching among substitutes during the course of the auction. Designing an auction to allow this is quite difficult. John Ledyard, a prominent economist at the California Institute of Technology, argued cogently that designs even more complex than the one adopted could be necessary if bidders required different combinations of licenses and if licenses were very much more valuable in these combinations than individually.

Besides the pattern of substitution and complementarity among licenses, another source of complexity arises from the fact that the licenses are to be used to create businesses for new services with uncertain technology and unknown consumer demand. Bidders in such an environment are likely to have widely divergent opinions about these critical business factors. In a poorly designed auction,

⁸July 23, 1994, page 70.

the ultimate license assignment could depend more on the bidders' optimism about the demand for future PCS services than on their abilities to create value. But a well designed auction process can mitigate that problem.

The auction design process began with a Notice of Proposed Rule Making (NPRM) issued by the FCC's Office of Plans and Policy in September of 1993. The NPRM asked for comments on a wide range of issues including what should be auctioned, what provisions should be made for bidders owned by small businesses, women, minorities, or rural telephone companies (the SWMRs, pronounced "swimmers"), and what the detailed rules for the auction would be. The NPRM also proposed a tentative auction format.

The NPRM proposed that the licenses be sold in a two-stage auction. In the first stage, bidders interested in establishing nationwide systems of service would submit sealed tenders to the FCC for a package of 51 licenses, each restricted to a geographical region called a major trading area (MTA). Together, the 51 MTA licenses would cover the entire United States. These tenders would remain sealed until the end of the second stage. In the second stage, the individual licenses would be auctioned in some predetermined sequence. Then, the sealed bids from the first stage would be opened and compared to the sum of the second stage prices. If the highest sealed bid were larger, then the whole package would be awarded as a package to whomever who submitted that bid. Otherwise, the licenses would be awarded to the highest individual license bidders from the second round.

This process would then be repeated for the B band licenses. Finally, the remaining licenses would be auctioned in sequence until all the licenses were assigned.

In complicated dynamical systems, small details often have large consequences. It is said, for example, that a butterfly flapping its wings in Beijing can start a process that results in a thunderstorm

in California a week later. The “butterfly effect” in the FCC auction began with the NPRM's careful footnoting of the auction theory literature. In retrospect, that literature was largely irrelevant for the FCC's problem, but the footnotes initiated a process. The potential bidders who examined the NPRM were mostly large telecommunications companies with no idea of how to evaluate the proposed auction design. Puzzled, they tracked down the names cited in the footnotes. For auction researchers around the United States, the phones began to ring.

Pacific Bell hired Stanford colleague Robert Wilson and me to review the NPRM on their behalf. When we tried to explain why they would be disadvantaged by this proposal on the basis of a subgame perfect equilibrium analysis, they weren't sure what to make of the analysis or of us. Deciding to put our theorizing to the test, they hired Professor Charles Plott of Caltech to design and run experiments testing our predictions. With limited time, the experiments were less than conclusive. Still, the results were generally consistent with the predictions we had made, boosting our client's confidence in us.

The outcome of the FCC's deliberations was the celebrated *Second Report and Order*,⁹ which established the FCC's policies regarding auction rules. As their primary auction method, the FCC adopted a *simultaneous, multiple round auction*. In a *simultaneous* auction, several licenses are sold all at the same time, as had happened in New Zealand. The *multiple rounds* part of the design meant that, after the initial round of bidding, the prices would be announced, and bidders would have an opportunity to raise their bids and to place new ones. This would be repeated round after round until, after a period of no new bids, the auction was declared ended.

⁹In PP Docket No. 93-253, regarding implementation of Section 309(j) of the Communications Act - Competitive Bidding.

The main advantage of this format is supposed to be that it allows the bidders to take account of interdependencies among the licenses. For example, if two licenses are perfect substitutes for a bidder, then the bidder can switch among the licenses during the auction, bidding to acquire whichever is cheaper. If two licenses are complements, then the bidder can take account of the high price of one license in determining how much it is willing to pay for the other. In terms of classical economic theory, the simultaneous auction was supposed to resemble the process that nineteenth century economist Leon Walras called a *tatonnement*, from which perfectly competitive prices and allocations are supposed to emerge.¹⁰

Simultaneous auction formats had been suggested several times before. At the FCC, economist Evan Kwerel, who had championed the use of auctions to sell spectrum rights, raised the possibility of a simultaneous auction format in the 1980s. In the months before the NPRM was issued, several other economists and game theorists had also advocated the use of some form of simultaneous auction. These early proposals, however, omitted any analysis of the critical details of how the auction should be conducted. Which licenses should be auctioned together? Should bidders be permitted to form bidding consortia? To bid for more licenses than they are actually eligible to acquire? To withdraw earlier bids as the auction proceeds? Should there be bid withdrawal penalties? Minimum bid increments? A time limit or a limit on the number of rounds? Deposits? If so, what should the withdrawal penalty or bid increment or time limit or deposit be? Should bidders' identities be made public or kept secret during the auction? How many rounds should be conducted each day, and how

¹⁰However, the *Walrasian tatonnement* process allows prices to go either up or down during the price adjustment, in contrast to the FCC auction in which prices can only rise. As discussed in chapter 2, this difference has important consequences both for the theory and for the practical implementation of the auction.

should that vary during the course of the auction? Should bidding be closed separately for each license, or all at once? Definite answers to these questions and many others were needed before a simultaneous, multiple round auction could be implemented. As U.S. Vice President Albert Gore remarked at the opening ceremony for the December, 1994 auction, "They couldn't just look it up in a book."

The developments that converted the simultaneous auction design from an academic proposal into a serious alternative were contained in the comments on the NPRM that Preston McAfee submitted on behalf of Airtouch (a cellular services provider) and that Robert Wilson and I submitted on behalf of Pacific Bell and Nevada Bell (local wireline telephone companies serving California and Nevada). These comments included detailed proposals. The Pacific Bell proposal also included a short manual outlining the required daily activities of the FCC and its auction contractor during the auction and indicating how the FCC might react to various emergencies, such as communications failures and earthquakes.

During the deliberations, the FCC staff emphasized that they did not wish to adopt a design requiring the creation of complicated new software within the tight time schedule required by the auction legislation. McAfee had anticipated the challenge and responded to it by designing a simultaneous auction that could be conducted entirely by hand if necessary. Wilson and I did not back down from a computerized auction. Instead, we asked our assistant, Zoran Crnja, to prepare an Excel spreadsheet program, in both PC and MacIntosh versions, that the FCC staff members could run to see exactly how the core auction software would operate. We hoped that working software, together with the long history of electronic auctions designed and conducted in economics laboratories, would convince the skeptics of the realistic possibility of implementing our computer-based auction procedure.

In the end, the FCC was convinced: it adopted the Milgrom-Wilson rules with only slight modification as its primary auction method. The FCC design included two features that had been almost unique to the Milgrom-Wilson proposal: First, bidding would not close on individual licenses until there were no new bids on any license.¹¹ In that way, bidders could come back to bid on licenses even after long periods of inactivity if the changing license prices made that alternative desirable. Second, there would be an "*activity rule*" requiring minimum levels of bidding activity from all bidders. Bidders who failed to maintain the minimum level of bidding activity would lose some of their eligibility for making bids in later rounds of the auction.

These two aspects of the Milgrom-Wilson proposal were complementary. With a simultaneous closing rule, bidders would not fear that individual licenses might close early. That allows bidders to execute back-up strategies if the most desired licenses become too expensive, but the ability to delay could also result in an impractically long auction. In addition, as the analysis in Chapter 2 will show, the presence of an activity rule can make it harder for bidders to cooperate in the auction to keep prices low. For if a bidder cuts back its activity in an attempt to encourage its competitors to reciprocate, it loses some of its ability to retaliate in case the competitor does not reciprocate.

Game theory played a central role in the analysis of rules. Starting from the Milgrom-Wilson proposal, every suggested rule change was tested by the FCC staff and the bidders' consultants in game-theoretic terms. We asked: What new strategic options does the change create for the bidders? How is it likely to affect the efficiency and revenue-generation of the auction? What is the worst case that the rules make possible? Could a rational bidder ever benefit by taking us down that path? Do our

¹¹A proposal by the National Telecommunications and Information Administration also appeared to include this feature.

discretionary rules allow us to avoid or recover from that scenario? The FCC hired its own expert, John McMillan, to assist in answering these questions, but it was also in almost constant contact with the bidders' consultants about the same issues. Ideas of Nash equilibrium, rationalizability, backward induction, and incomplete information, though rarely named explicitly, were the real basis of daily decisions about the details of the auction design.

As an example of a review of proposed rules from a strategic game perspective, consider the discussion of how to handle withdrawn bids. The Milgrom-Wilson rules did not permit bid withdrawals. Bidders whose business plans called for assembling nationwide combinations of licenses complained that such rules could create a serious problem for them. If they bid aggressively for the whole desired collection of licenses, they might find themselves as the high bidder for some licenses when others had become too expensive, leaving them stuck with an unwanted license assortment. In response, a rule change was suggested to permit bidders to withdraw bids freely so that they could protect themselves from this outcome. The idea was that such a rule change would free bidders to be more aggressive, resulting in a better assignment of licenses and higher prices for the government.

The proposal to allow free bid withdrawals might seem to be a plausible compromise that addresses a valid concern and could even lead to higher prices. To those trained in game theory, however, it was obvious that such a rule change would devastate the effectiveness of the auction. With the original Milgrom-Wilson rules, a bid is a real commitment of resources, not something that can be made lightly. With free bid withdrawals, bids lose much of their meaning. A bidder could bid \$500 million for a license and let others plan on that basis, then withdraw the bid and switch to something else, upsetting other bidders' plans. There are no such opportunities to upset competitors' plans in the original auction proposal. A second serious defect of the proposed rule change is that makes the length

of the auction indefinite. Under the original rules, prices rise continuously. That, plus the required substantial deposits to discourage frivolous bids, guarantees that some bidders will eventually drop out and the auction come to a close. With free bid withdrawals, however, the progress of the bidding could be highly erratic, with total prices rising and falling along the way. The length of the auction would become indefinite. Worse, the auction would become vulnerable to a bidder intent on mischief who could, for example, postpone the auction's closing for as long as desired by the simple expedient of repeatedly making and withdrawing bids.

Understanding all these problems, economist and game theorist Preston McAfee suggested a compromise rule: a bidder who withdraws a bid would be subject to a penalty. The penalty would be equal to the larger of zero or the excess of the withdrawn bid over the final license price. Such a penalty protects the government from bid withdrawals since each bid is a guarantee of revenues for the government. With such a rule, the total promised revenues can only climb during the auction, helping to ensure the auction's timely close. Because the rule helps to ensure that bidders think seriously and avoid frivolous or mischievous bids, the actual penalties that the rule would be expected to impose should be only small fraction of the total auction revenues. In view of these advantages, the FCC adopted the McAfee withdrawal rule, which eventually worked much the same in practice as in theory.

The resulting auction rules were imperfect in several ways. Since there are bid withdrawal penalties, the problem of bidding for combinations of licenses remains. Theory suggests that when complementarities among licenses are important, this is a genuinely hard problem. As we shall see in chapter 2, it may even be impossible for any mechanism that works by pricing individual licenses to lead to an efficient license assignment. Still, the auction designers decided that the complementarity

problem was small enough that these rules were still likely to succeed in the FCC's planned applications.

The Narrowband Auctions: Trying Out the Simultaneous Auction Design

Because the design was so new and the stakes so large, the FCC decided to proceed cautiously in implementing it. The first simultaneous, multiple round auction was supposed to be a relatively small scale trial, involving licenses estimated beforehand to be worth only about \$50 million. Ten licenses to be used for nationwide paging and voice messaging services were offered for sale. Although the auction was formally designated as "Auction #1," it was widely known as the "Nationwide Narrowband Auction." "Narrowband" referred to the fact that the bands of spectrum allocated for paging and messaging services were much narrower than those allocated for wireless telephone, fax and data services, while "nationwide" referred to the geographic scope of the individual licenses offered for sale. Licenses with numbers N1 to N5 in the auction were the most valuable ones, each comprising 50 kHz of spectrum that could be used to send "outbound" messages to pagers and a 50 kHz "return" channel for reply messages. Licenses with numbers N6 to N8 were in the next stratum of value, with a 50 kHz outbound channel and a 12.5 kHz return channel. The last two licenses were numbered N10 and N11,¹² containing a 50 kHz outbound channel. Within each category, licenses were nearly perfect substitutes, except that a company acquiring two or more licenses would benefit from having consecutively numbered licenses, which occupied adjacent portions of the spectrum.¹³

¹²License 9 had been previously awarded outside the auction process.

¹³The reason is that there is a small buffer band to prevent interference between adjacent areas of the spectrum. A company acquiring two adjacent bands could use the buffer band to increase the capacity of its paging services.

The auction began on Monday morning, July 25, with bids that shocked observers. Even though no bidder was eligible under the FCC rules actually to acquire more than three licenses, nothing in the rules prevented them from bidding on more than three licenses. Two bidders took advantage of that flexibility, opening with bids on all ten licenses. McCaw Cellular's ten bids, which totalled \$78.75 million, pushed the opening prices beyond what the pundits had anticipated for the final round of the auction. One week later, when no new bids were received in round 47, the auction closed. The final prices totaled \$617 million, setting a new U.S. record for revenue from a sale of public assets.

Table 2

Results of Nationwide Narrowband Auction (Prices in Millions of dollars)		
License #	Bidder	Final Price
1	PageNet	80.00
2	PageNet	80.00
3	McCaw	80.00
4	McCaw	80.00
5	Mtel	80.00
6	Airtouch	47.00
7	Bellsouth	47.51
8	Mtel	47.50
10	PageNet	37.00
11	PageMart	38.00
Total		617.01

Table 2 summarizes the outcome of the auction, reporting the identities of the highest bidders and the amounts of their bids. Just as for the New Zealand auction, it is impossible to determine

conclusively whether the license assignment in this auction was efficient. Nevertheless, there are several indicators available, and all point to an efficient outcome. First, the two companies that purchased bands 1-4 each acquired a pair of adjacent bands, as is required for technical efficiency. Second, in contrast to the New Zealand experience, the prices of similar licenses in the FCC's nationwide narrowband auction were very close. Indeed, the first five licenses closed at identical prices of \$80 million each, and the largest difference among the prices of the other groups of near-perfect substitutes is just three percent. This evidence of arbitrage suggests that bidders were in a good position to compare prices and values and to change their demands accordingly. This conclusion is reinforced by analyses of the price differences among different kinds of licenses and by studies of the bidding dynamics, which confirm that bidders compared prices across different types of licenses and switched among them when that made economic sense. Third, both the final results and the detailed auction analyses indicate that bidders gained little or no advantage from jump bids and other stratagems. Indeed, the evidence indicates that jump bidding could be a costly ploy: the largest price anomaly in the auction was the \$38 million price paid for band 11, when band 10 sold for just \$37 million. The \$38 million price resulted from a jump bid by a bidder who appeared to be trying to establish the seriousness of its commitment to the license.

It is not economic but political criteria, however, that were used to judge the auction in Washington. Fortunately, the political indicators of auction performance looked good, too. First, the auction procedures and software ran smoothly, avoiding second-guessing by those who argued that the rules were too complicated to be administered successfully. Second, the revenues from the auction were unexpectedly high. Ironically, this was the most important factor in the public perception that the auction format was a success, even though the revenue surprise resulted much more from errors made

in estimating license values than from any particular features of the auction rules. Finally, bidders interviewed by the FCC staff during and after the auction reported that they were generally satisfied, though some wished the pace had been a bit faster. Even the winning bidders' executive officers, who had paid the unexpectedly high prices, were happy with the auction. The reason is easy to understand: Unlike a sealed bid auction in which a bidder has to guess how much the competitors are bidding, bidders in this auction were not in danger of paying far more than necessary to acquire a license. They could explain to their shareholders that the prices were outside their control and that others who had acquired similar kinds of spectrum had paid just as much.

Inside the FCC, the reaction was a mixture of relief and euphoria. The chairman of the FCC, Reed Hundt, captured the mood of many when, halfway through the auction, he told reporters: "Looks to me like it's a blockbuster hit."

In the public eye, the nationwide narrowband auction was often compared to the concurrent auction #2, which sold licenses for interactive video and data services (IVDS). Auction #2 was conducted using English auction rules, with the licenses being sold one at a time by oral outcry. Participants' deposits, at \$2500 per five licenses, were small compared to the auctions prices, some of which exceeded \$1 million. Many of the buyers in this auction were speculators. Some masqueraded as woman- or minority-owned bidders in hopes of qualifying for special discounts. Several of the bidders, unhappy that they had paid more for their licenses than others paid for similar licenses later in the auction, chose to default on their bids. To public observers comparing auctions #1 and #2 side by side, the contrast was sharply drawn: auction #1 was indeed a "blockbuster hit."

The second trial of the simultaneous, multiple round auction design began on October 26, 1994. Thirty licenses were offered for sale in this "regional narrowband auction," formally identified as

auction #3. As in the national narrowband auction, the spectrum offered was for use in paging services. Unlike the nationwide narrowband auction, however, the licenses sold in this auction did not cover the entire nation. Instead, they covered five regions of the U.S. each with a population of about 50 million people. For some companies, the regional licenses fit the business plans well, but companies wishing to provide a nationwide paging service would need to acquire all five regional licenses in a single spectrum band. There were six spectrum bands offered. Bands 1 and 2 comprised a 50 kHz outbound and a 50 kHz return channel, while bands 3-6 comprised a 50 kHz outbound channel and a 12.5 kHz return channel.

An important detail of the design of the second auction was the nature of the special advantages provided for small businesses and woman- and minority-owned bidders. All three types of bidders were eligible to receive preferential financing terms for any licenses they acquired. Also, the woman- and minority-owned bidders were to receive 40% discounts for any licenses they acquired in bands 2 or 6. In practice, this discount was so large that the auction can be analyzed as if only minority bidders were eligible to bid on licenses in bands 2 and 6.

The auction closed on November 8, after 104 rounds. Table 3 shows the results. Several aspects of the results stand out. In bands 1-4, bidders whose business plans required a nationwide collection of licenses succeeded in acquiring the five regional licenses in a single band. This was an extremely important aspect of the outcome, since one of the key advantages of the simultaneous auction is supposed to be that it facilitates competition between regional and national competitors without being biased against either. The ability of companies planning nationwide paging services to assemble efficient national packages of licenses under these auction rules confirms the auction effectiveness in that regard.

Table 3:
Regional Narrowband Auction Results

Winning Bidders by region and spectrum block

	1	2*	3	4	5	6*
N.E.	Pagemart II	PCS Dvlpmt	Mobile Media	Advanced Wireless	Airtouch	Lisa-Gaye Shearing
South	"	"	"	"	Insta-Check	"
Midwest	"	"	"	"	Ameritech	"
Central	"	"	"	"	Airtouch	Benbow
West	"	"	"	"	"	"

*Discounted Final Prices by region and spectrum block
(Results in Millions of Dollars)*

	1	2*	3	4	5	6*	Total
N.E.	17.50	14.85	9.47	8.95	8.68	10.25	69.70
South	18.40	18.78	11.80	11.54	8.00	11.26	79.79
Midwest	16.81	17.36	9.29	10.06	9.50	10.25	73.27
Central	17.34	17.14	8.25	8.79	8.26	10.49	70.27
West	22.55	22.80	14.86	14.28	14.28	10.92	99.69
Total	92.60	90.93	53.67	53.62	48.72	53.17	392.71
July Price	80.00	80.00	47.34	47.34	47.34	47.34	349.35

* = Blocks benefiting from the 40% woman/minority discount.

Also, the net, after-discount prices of the licenses targeted for woman- and minority-owned bidders were about the same as the prices for the other licenses. The winning minority bidders in this auction included PCS Development Corporation, Lisa-Gaye Shearing, and Insta-Check. The fact that a minority-owned bidder was able to acquire a license for which no discount was offered indicates that there was excess demand for the reserved licenses. If arbitrage were possible, as the designers intended,

then there should be no net discount. The fact that there was none is evidence that arbitrage was possible in this design.

The table also shows that the arbitrage among similar licenses was imperfect. In view of the advantage to acquiring licenses in a single band, none of the individual licenses are perfect substitutes, though certain packages of licenses are. Given the auction rules, which penalize bid withdrawals, the opportunities to execute an arbitrage strategy across packages of licenses is limited, allowing some price variation between similar licenses to emerge. Nevertheless, the price variations between similar nationwide packages of licenses are small, with only band 5 being more than three percent different from the comparable packages. Half of that low price anomaly is due to the very low price of the southern region in band 5, which resulted from a withdrawn bid late in the auction.

Finally, the table also shows that prices were significantly higher in the October auction than they had been in the July auction (auction #1). The last line of the table shows the average price of a comparable national license purchased in July, which can be compared to the total price of the regional licenses in each spectrum band. It is unlikely that changes in conditions account for the increase in prices from July to October. Bidders like Pagemart and PCS D simply had to guess whether to bid more aggressively in July, or to wait and hope for a better value in October. Despite the higher prices they paid, it is not clear that they guessed wrong, for if they had tried to acquire more licenses in July, those prices would have been driven up, too.

There is one clear loser from the price change: the federal treasury. According to economic theory, the actual market values of identical licenses should be the same and the last licenses sold usually give the best estimate of those values, because the last prices are determined by the value of the last bidder to drop out of the bidding. If the licenses had all been sold at once in a single simultaneous

auction, it is likely that all the prices would have been at the October levels, increasing the total auction revenues by about \$77 million. Nevertheless, there should be no criticism of the FCC on this account. The novelty of the auction design and the need to test the auction procedures and software made it seem prudent to FCC insiders to start with a small auction, despite the likely loss of revenues and efficiency.

Gaming Behavior in the Regional Narrowband Auction

The usefulness of game theoretic analysis in assessing auction designs is definitively confirmed when one studies the auction dynamics closely, examining the many attempts to "game" the rules. In the regional narrowband auction, there were strategic bids made that served at least five different purposes. (1) Jump bids established commitment to a particular band of spectrum or to control the pace of the auction; (2) "predatory" bids drove up a competitor's price or disrupted its attempts to establish a system of licenses (a "footprint"); (3) temporizing bids avoided bidding wars while still maintaining required levels of activity and keeping the auction from closing; (4) retaliatory bids punished bidders for unwanted competition in particular markets, and (5) one bid appears to have been intended to provoke a retaliatory response. Some bids may have served more than one of these purposes.

The regional narrowband auction opened with several jump bids, most notably those by a minority bidder – the PCS Development Corporation (PCSD), which opened by bidding \$16 million for each of the five regional licenses in band 2. The \$80 million total was nominally the same as the price paid for the similar national licenses in the July national narrowband auction. However, since PCSD was entitled to a 40% discount on its bids, the effective bid was 40% less than the final bids in

the July auction. PCSD responded to each challenge in the first fifteen rounds by another jump bid, as if to assert that it intended to meet all challenges to the spectrum it had chosen for itself.

Band 2 was not the only one to receive jump bids. In band 1, Pagemart and its competitors jumped by smaller amounts as they sought to establish which of them would acquire the valuable band 1 spectrum and which would have to settle for less valuable licenses in bands 3-5.

The early round jump bids in this auction functioned much as they had in the July narrowband auction; they helped to establish quickly which bidders were laying claim to which licenses. That was important in the regional narrowband auction, where bidders sought to aggregate the spectrum from several regions to form what was effectively a national license.

As the auction progressed, it quickly became clear that the minority license prices were going to be comparable to the other license prices. At round 30, minority bidder PCSD decided to test the resolve of one of non-minority bidder Pagemart by entering a bid of \$18.6 million for the western band 1 license. For nearly the same price, PCSD could have bid instead on the western license in band 2. Also, bidding for band 2 would have made more sense in view its other bids, which covered all the other regional licenses in band 2. When Pagemart bumped PCSD's bid at round 31, PCSD bumped back at round 32. In doing so, it bid more than the minimum necessary bid for the band 2 alternative. This may have been a predatory bid, aimed at driving up Pagemart's price, although it might be rationalized as an attempt to explore whether a package comprising band 1 licenses would be cheaper than one comprising band 2 licenses.

PCSD's aggressive bidding left Pagemart vulnerable. As the band 1 leader in the other regions, Pagemart needed a western license to complete its nation-wide collection. It could not retaliate against PCSD in band 2 because, as a non-minority, it was effectively banned from bidding there. It appeared

that PCSD could test Pagemart and drive up its price and then return to purchase the band 2 license at a lower price – perhaps much lower. And, if that worked, PCSD might even repeat the stratagem as a predatory strategy, for example by bidding to drive up the price on the southern region, band 1 license.

Pagemart responded to the challenge by letting PCSD remain the high bidder on the relatively expensive band 1 license while it pretended interest in bands 3 and 4 from round 32-46. There is strong circumstantial evidence that this interest was feigned. For example, in rounds 40 and 42, Pagemart raised its own bid for the license in the western region, band 4. Why would Pagemart do that? It appears that Pagemart expected to be outbid for those licenses eventually, but feared that the auction might end before it could return to bid again against PCSD in band 1. Since the closing rule specified that the auction closes when there is a round with no new bids, Pagemart bumped its own bid to ensure that the auction remained open.

There is additional evidence to support that interpretation. In every round from 33-46 and again from 48-62, Pagemart submitted at least one new bid, evidently to keep the auction from closing. Why didn't it bid at round 47? Because it wanted the auction to close then, with no new bids at that round. For after only two new bids besides its own were submitted at round 45, Pagemart bid at round 46 to recapture the western band 1 license. It was not to be. At round 47, PCSD again bumped Pagemart's bid, offering \$1.9 million more for the western band 1 license than the price for the corresponding and more suitable band 2 license.

As the auction entered stage 3 at round 74, Pagemart appeared to become increasingly desperate. As its behavior in the next several rounds shows, Pagemart carefully maintained activity on three 50/12.5 licenses at each round in order to be eligible to bid on the two 50/50 licenses in band 1 that it really sought later in the auction.

Eventually, Pagemart's bidding on licenses outside its real interests proved costly. It was forced to withdraw its bid on the southern license for band 5, incurring a withdrawal penalty of over \$2 million and resulting in the pricing anomaly that was mentioned earlier.

Perhaps the cleverest instance of strategic bidding in the auction was the stratagem rumored to have been executed by Lisa-Gaye Shearing. At round 54, Shearing disrupted PCSD's band 2 nationwide aggregation with a bid for the midwestern regional license. True to its previous bidding patterns, PCSD retaliated with a bid on the western license for block 6, where Shearing had the standing high bid. In the auction room, the Shearing representative reacted with glee! Shearing never again bid on the western region, band 6 license. Evidently, Shearing wished to withdraw from that license without incurring a bid withdrawal penalty, and it accomplished that goal by intentionally attracting PCSD's retaliatory bid!

Tinkering with the Rules

Although most public observers thought that the two narrowband auctions had run well, FCC insiders were concerned that the auctions were taking too long. After all, if auctions of just 10 and 30 licenses had taken 46 rounds and 104 rounds respectively, how many rounds would be required by the much larger broadband auctions, in which the numbers of licenses to be sold might exceed 1000? The auction scheduled to begin on December 5, 1994 would involve 99 of the most valuable spectrum licenses, and initial proposals had called for just one or two rounds per day. These relatively infrequent rounds were supposed to ensure that the bidders, some with individual bids in the hundreds of millions of dollars, would have time to evaluate the bids after each round and make their plans for subsequent bidding. Yet, if more than tripling the number of licenses from 30 to 99 tripled the time required and

resulted in an auction of, say, 300 rounds, then even at two rounds per day, five days per week, it would take more than six months to complete, delaying the issuance of the licenses and the introduction of PCS services. Given the FCC's desire to see a prompt roll-out of PCS services, a six month auction was simply too long.

Once again, careful theoretical analysis provided a sound underpinning for setting the rules, although this time it was not game theory that was decisive. Electronic messages among the auction consultants with copies to the FCC engaged the academic experts in a discussion.

There seemed to be general agreement among the experts that the length of the auction could be shortened in four different ways: imposing a minimum initial bid, increasing the minimum bid increments, increasing the activity rule percentages, or raising the number of bid rounds per day. The first of these options was excluded under the FCC's written rules. Of the remaining three options, my own analysis concluded that raising the minimum bid increment was the most promising approach for auction #4. Using reasoning much like that of the "Harberger triangle" of market theory, I calculated that the expected loss of efficiency from using a given bid increment would be on the order of the square of the bid increment. Indeed, a 5% bid increment could result in an inefficient license assignment in a single object auction only if the bidders' valuations lie within 5% of one another, and even then only half the time and with a loss in value of at most 5%. Calculations based on this analysis put the expected efficiency loss from a 5% bid increment at less than 0.01% of the license value, which is negligible in terms of the other costs and losses incurred during the auction. By my calculation, the effect of a larger bid increment on the government's expected revenue would be of a similarly small magnitude.

Besides increasing the bid increment, another effective way to increase the pace of the auction would be to increase the number of rounds per day. So long as the number of rounds per day is kept small enough to allow the bidders to process information and submit bids, this is a pure efficiency gain with no cost to the process. However, in view of the novelty of the auction procedures, none of the auction advisers were sure how quickly bidders could process information. Given the high stakes of the broadband PCS auction, it seemed a poor time to explore the limits of round frequency. Consequently, we recommended that the rounds be kept to two per day, and we recommended that the number of rounds per day be just one in periods with high levels of bidding activity.

Use of an increased activity requirement to raise the pace of bidding early in the auction seemed the worst option, for it can force bidders to commit to a level of activity before any reasonable estimates of the license prices can be made. According to economic theory, decisions based on such guesswork are likely to be mistaken, damaging the efficiency of the license assignment.

With the various expert analyses at his disposal, the FCC's Evan Kwerel engineered a switch from the 2% bid increments of the regional narrowband auction to 5% increments in the December auction, although a few rounds were conducted with even larger 10% increments. The increased increments reduced the estimated number of rounds in the auction by 60%. The actual number of rounds in the completed auction was 112, establishing the importance of the increased bid increment.

Although the bid increment decision was the most important modification of the auction design made by the FCC between the two auctions, there were two other important decisions that could have been devastating if they had been botched. One of these concerns the lengths of the rounds, about which a wide range of opinions was expressed. The FCC chose to retain its discretion to modify the number of rounds per day during the auction. Rounds were held at a rate of one per day during the first

few rounds of each stage and two per day the rest of the time. (Only as the auction approached its close did the FCC announce plans to conduct three rounds per day, beginning with rounds 110-112, but there were no new bids at round 112.) The extra time at the beginning of each stage was included to account for the increased bidding activity that was bound to occur at those times. The increased activity would give the bidders more to think about, so it seemed prudent to allow them more time then. (For later auctions, now that the bidders' routines for reporting information and making decisions are well established, it is possible and probably desirable to increase the number of rounds per day.)

One other decision proved particularly critical. During the two narrowband auctions, bidders had mostly been much more active than the minimum levels required by the activity rule. With this experience in mind, GTE had advocated repealing the activity rule to allow bidders more flexibility. As discussed below, GTE's bidding strategy appeared to involve lying low early in the auction in order to conceal its intentions from other bidders. The activity rule works against such a strategy by forcing a bidder to be active early in the auction, and that probably accounts for GTE's position on this matter of rules. However, the FCC rejected GTE's request and retained a rule that would prove critical in the actual conduct of the auction.

“The Greatest Auction in History”

The long anticipated auction #4 opened on December 5, 1994. It was an event that the telecommunications companies, regulators, and economists had eagerly anticipated, for the stakes were huge and the bidders included most of the United States' largest telecommunications companies. For sale were 99 licenses to be used mostly for wireless telephone applications. The wireless telephone market is important in its own right, involving annualized revenues of \$6.5 billion by mid-1994. These revenues had been growing at 35% per year for the past decade and at 50% in the most recent twelve months, and were expected to continue growing rapidly for most of the next decade as well. In an era of deregulation where the expectation is that, soon, the only profitable long-distance carriers will be those with direct access to final consumers, wireless telephones provide a critical new technology for reaching those consumers.

The 99 licenses offered for sale in the auction covered the 51 major trading areas or MTAs, as defined by Rand-McNally. Despite the number 51, the MTAs do not correspond to states, but rather to the area surrounding a single center of business activity. For example, the Los Angeles MTA covered not only all of southern California, but also southern Nevada (including Las Vegas) and a portion of Arizona. Northern California and much of northern Nevada were included in the San Francisco MTA.

Table 4: Biggest Spenders in Auction #4

Bidder	Exposure (\$ millions)	Population (Millions)
Wireless*	2,110.0	145.1
AT&T	1,684.4	107.1
Primeco	1,107.2	57.1
Pacific Bell	695.7	31.0
GTE	398.3	19.3
American Portable	288.9	26.5

*Wireless's business partners acquired licenses covering another 37.5 million people, for a total covered population of 182.6 million.

The MTAs are large geographical areas, with an average population of about five million people, although there was a lot of variation about that mean. The largest MTA (New York) has a population of over 26.4 million people, while the smallest (American Samoa) has a population of 47 thousand. There are two MTA-wide spectrum bands, labelled A and B, available in each MTA, so there are 102 licenses in all. Of these, three licenses (covering the New York, Los Angeles and Washington MTAs) were awarded outside the auction. This left 99 licenses for assignment by the auction.

The high value of the individual MTA licenses was linked not only to the population sizes but also to the bandwidth of the spectrum being sold, which was 30 megahertz of spectrum in the 2 gigahertz frequency range. This bandwidth is comparable in its capacity to carry telephone signals to the bands currently used for cellular telephone service. Depending on the efficiency of the technology used and on the number of cell sites, these bands can support large numbers of customers making phone calls simultaneously.

The exceptionally high value of these licenses made auction #4 the FCC's most closely watched auction. To the disappointment of outsiders, bidding in the auction began slowly. The sums at stake were very large, and bidders were quite uncertain about the likely eventual price level. According to the activity rule that applied in this auction, to be eligible eventually to acquire licenses covering, say, 120 million people, a bidder needed to be active on licenses covering only 40 million people during stage one of the auction. This three-to-one activity requirement allowed bidders to be quite patient, bidding on much less spectrum than they eventually hoped to acquire while carefully watching other bidders to learn what they wished to acquire and how much they were willing to pay. With most big bidders adopting this wait-and-see attitude, new bidding activity came to a virtual halt with only two new bids in round nine, one in round ten, and three in round 11 of the auction. With prices much lower than most pundits had forecast, Justice Department lawyers and lay critics were quick to suspect that the bidders must be colluding, refusing to bid against one another to drive up the prices.

In fact, however, the behavior that was occurring was one of the patterns that Robert Wilson and I had forecast for situations in which the number of bidders is small. Many bidders had adopted "wait-and-see" strategies, as permitted under the auction rules.

To analyze this situation, we had proposed that the government compute the ratio of the total initial eligibility of bidders to bid on licenses to the number of licenses available, adjusted to reflect the sizes of the populations covered. These are measured by "POPs," the standard unit in the industry.¹⁴ At the beginning of the auction, this "*eligibility ratio*" was 1.93. Each bidders' initial eligibility was determined as the size of its deposit (in dollars) divided by .6. Under the activity rule at the auction

¹⁴For auctions in which the license bandwidths differ, we proposed using the product of the bandwidth and the covered population, employing units we called "MHz-pops."

opening, it was possible for each bidder to retain its full eligibility by holding the highest bid on 1/3 of the spectrum in which it had expressed an interest. So, in the actual circumstances, it was possible for each bidder to be "active" on the requisite amount of spectrum by holding the highest bid on some license from the preceding round without having to make any new bids. It was this wait-and-see behavior, rather than any collusion among bidders, that led to the stalling of the auction in its early rounds.

At round 12, the FCC declared that the auction was in stage 2. This meant that a bidder who wished to remain eligible for licenses covering 120 million people now had to be active on licenses covering at least 80 million people. The response was immediate, as bidders wishing to retain their eligibility increased their levels of activity. Figure 1 shows the sudden increase in bidding activity when the stage 2 and stage 3 rules were implemented at rounds 12 and 65. Within each stage, it also shows the close connection between the declining eligibility ratio and the declining level of new bids. The Figure also shows that new bidding activity approached zero in stage 2 as the eligibility ratio approached 1.5. This outcome reflects the simple fact that bidders were bidding on just enough licenses to retain their existing levels of eligibility. Finally, the Figure shows the steady decline in the eligibility ratio during the auction that marks the auction's progress and allows bidders to make tentative price forecasts. The activity rule, combined with the bid increment rule, kept the auction to a manageable length of 112 rounds.

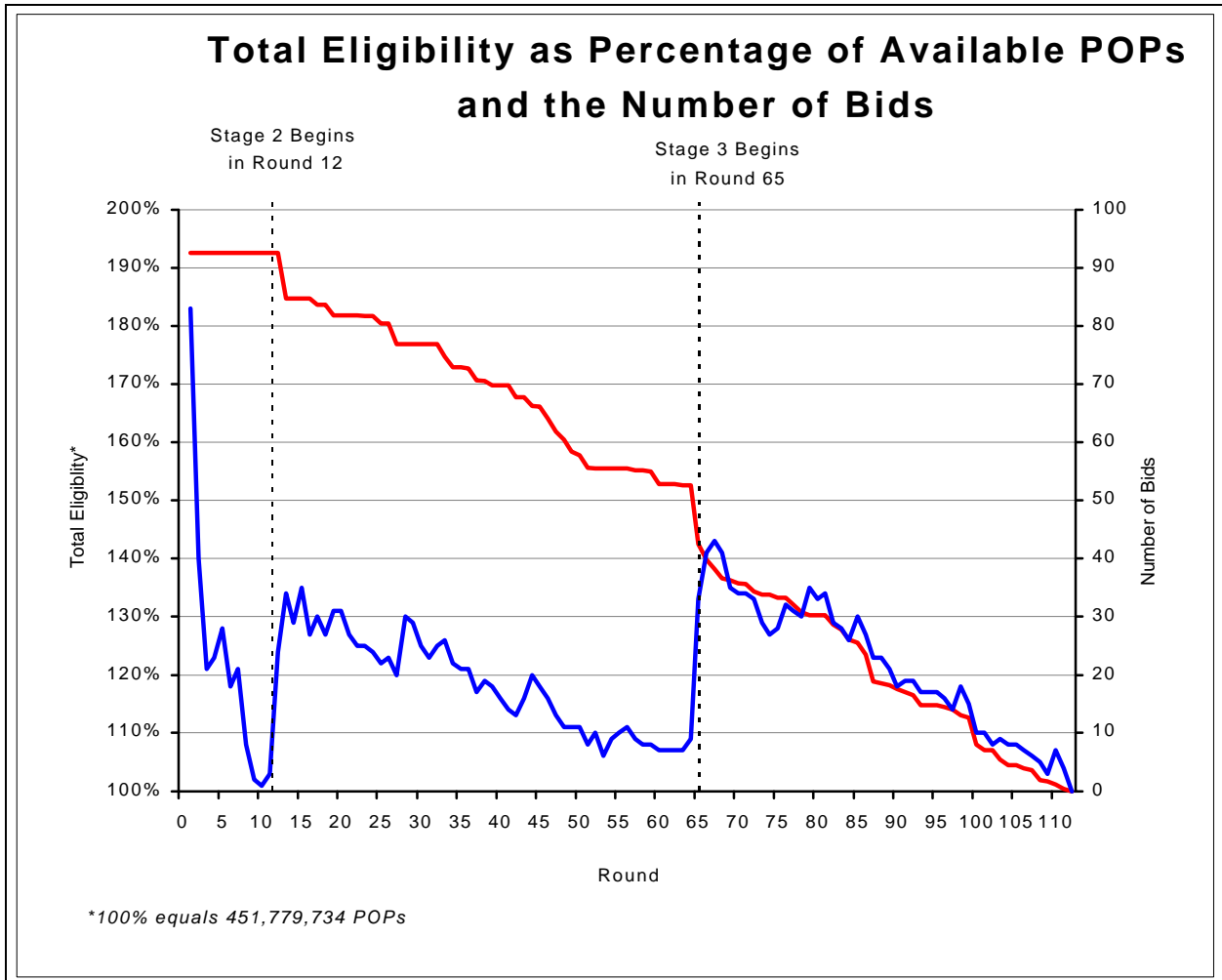


Figure 1

When bidding finally closed, direct revenues from the auction had exceeded \$7 billion. A formula applied to the auction prices determined the prices of the three excluded A-band licenses (New York, Los Angeles and Washington, D.C). These three licenses added another \$700 million to the auction revenue.

Bidder Strategy in the Broadband Auction

One of the hopes of the auction designers was that the auction would encourage most bidders to participate in a straightforward way, bidding for the licenses that appeared most valuable to them, so that the final license assignment would primarily reflect the bidders' actual values. There is evidence that many bidders did indeed adopt such straightforward strategies. Table 5 contains a list of the bidders who bid on the properties that interested them in round 1 and never bid on anything else.

Table 5: The Non-Strategic Bidders

The following bidders never became active on new licenses after the first round of the auction.

<u>Bidder</u>	<u>Major Trading Area(s) of Interest to the Bidder</u>
Ameritech:	Cleveland and Indianapolis
Bellsouth:	Knoxville and Charlotte
Boston PCS:	Boston
Centennial:	Puerto Rico
Cleveland PCS:	Cleveland
Comcast:	Jacksonville
Comm Int'l:	American Samoa
Cox:	Omaha and Richmond
Datalink:	American Samoa
Phillieco:	Philadelphia
Powertel:	Jacksonville, Birmingham, Memphis, New Orleans, Atlanta

In addition to these bidders, three of the four largest bidders adopted strategies that, while not so transparent as those just described, still appeared to reflect values in a straightforward way. The second largest bidder in terms of both total price paid and population covered was American Telephone and Telegraph (AT&T). By round 15, it had bid on all but two of the licenses that it would ever bid on. AT&T maintained a steady and mostly predictable pattern of bidding throughout the auction, adding bids only on the Omaha and Richmond licenses in rounds 40 and 65, respectively. These late additions seemed to reflect the fact that these licenses were selling for attractively low

prices, and AT&T did go on to acquire these licenses. The third largest bidder was Primeco, a consortium of four telephone companies (Airtouch, Bell Atlantic, Nynex and U.S. West) with extensive cellular operations. With the single exception of a bid on the Louisville license at round 50, Primeco had, by round 13, bid on all of the spectrum licenses that it would ever bid upon. Finally, the fourth largest bidder, Pacific Bell, opened by bidding on the Los Angeles and San Francisco licenses on which its interest had long been known. It flirted with the related Phoenix and Seattle licenses in the early rounds when prices looked cheap, but retreated to the two California licenses as prices in Phoenix and Seattle rose.¹⁵

The strategies adopted by the other largest bidders – Wireless, GTE, American Portable and ALAACR – were more complicated. ALAACR and American Portable are included in this list of large bidders even though ALAACR did not acquire any licenses in the auction and American Portable acquired mostly smaller licenses. In any auction, the most aggressive losing bidder has the biggest influence on prices. As Table 6 shows, ALAACR's and American Portable's influences were widely felt in the bidding for the most valuable licenses.

¹⁵These observations are also consistent with the hypothesis that the bidders wanted to divide the markets among themselves, made their preferences known early, and then accommodated one another. The process of accommodation, however, is difficult to coordinate without leaving some trace patterns of retaliatory bidding which is notably absent for this group of bidders.

Table 6: The Major Market Price Setters
Last Non-Winning Bidder by License

License	Bidder
#1 NY	ALAACR
#2 LA	ALAACR
#3 Chicago	WirelessCo
#4 SF	American Portable
#5 Detroit	American Portable
#6 Charlotte	CCI

License	Bidder
#7 Dallas	ALAACR
#8 Boston	Boston PCS
#9 Philadelphia	GTE
#10 Washington	American Portable
#11 Atlanta	Powertel
#12 Minneapolis	Continental

ALAACR bid on licenses in 18 MTAs but acquired none.

*American Portable bid on licenses in 29 MTAs and acquired 8:
Minneapolis, Tampa, Houston, Pittsburgh, Kansas City, Columbus, Alaska and Guam.*

Most inferences one can make about the strategic motivations of these large bidders are really just speculation, inferred from the patterns of bidding. The only significant exceptions are the remarks about GTE. A member of GTE's bidding team has published an insider account of GTE's preparations and analysis during the auction. Besides that direct testimony, there is evidence from the bidding itself that other bidders were not adopting the straightforward strategy of simply bidding on the licenses that were of greatest value to them.

Wireless was the most active bidder in seeking to exploit the rules of the auction to protect its position and to manipulate other bidders. In its competition with ALAACR – a company formed for the PCS auction by cellular telephone magnate Craig McCaw – for the New York license, Wireless postponed the direct competition until late in the auction. Probably, Wireless feared a pattern of retaliatory bidding in which ALAACR might respond to competition in New York by bidding up

Wireless's prices in other MTAs. It avoided that by waiting until late in the auction when ALAACR had too little flexibility to adopt such a strategy.

Wireless and GTE were both active in making bids for licenses that did not seem to be of direct interest to them. Both companies were believed to face limited budgets compared to the sets of licenses in which they were potentially interested and costs of building the infrastructure for their wireless systems. Perhaps both feared that their relative financial weakness made them targets for aggressive bidding strategies, in which a competing bidder might drive up the prices of licenses that Wireless and GTE needed in order to reduce the budget they had available to bid on other licenses.

Insider David Salant's account reports that GTE's goals early in the auction were to "[a]void bidding on target markets, partly to keep rivals from guessing that GTE's target markets were Atlanta and Seattle, (2) [m]aintain eligibility, and (3) [p]ush up the price in non-target markets, partly to avoid pushing up the price in target markets and partly to induce rivals to spend more money on those markets."¹⁶ The point of keeping rivals guessing was that "[h]ad we not done so, we might have been taken advantage of by others who wished to use up our budget." Thus, GTE's strategy appears to have shared several key elements with the strategy adopted by Wireless.

The evidence that Wireless engaged in strategic bidding consists of an analysis of episodes. One is the set of the jump bids by Wireless in rounds 79 and 81 for the licenses in Pittsburgh, Des Moines, Kansas City and Oklahoma City. At those rounds, Wireless significantly increased the license prices, raising them by a factor of nearly two to the range of \$7 per person in the covered population. These

¹⁶David Salant, "Up in the Air: GTE's Experience in the MTA Auctions for PCS Licenses," working paper, Charles River Associates.

bids raised its own costs as well as those of its rivals. Clearly, such bids must have been made with a strategic intent, but what intent?

The answer seems to be that the jump bids were calculated to discourage competitors from adopting certain strategies that would have been even more costly to Wireless. Wireless may have feared that its competitors would try to drive up its prices for other licenses in order to reduce the budget it had remaining to acquire licenses in Pittsburgh, Des Moines, Kansas City and Oklahoma City. From its competitors' perspective, such a strategy could appear to be an effective way to reduce the competition for those four licenses. How could it discourage such a strategy? By bidding up the prices of the four affected licenses ahead of time! Of course, this stratagem was costly to Wireless, raising its own prices and eventually saddling it with a bid withdrawal penalty. Still, the bidding team apparently believed that such a strategy would save more than it cost.

American Portable and Wireless had several interesting strategic encounters during the auction, but the most interesting of these is the apparent market division they made in their bidding on the San Francisco, Houston and Tampa licenses. Early in the auction, American Portable had bid actively against Wireless for the Houston and Tampa licenses, but the prices rose as Wireless bid determinedly, and American Portable eventually shifted its interest. Later in the auction, American Portable was engaged in a battle with Wireless for one of the San Francisco licenses.¹⁷ At round 97, after being outbid by American Portable in San Francisco, Wireless withdrew its leading bids in Houston and

¹⁷Pacific Bell and ALAACR were also active in the San Francisco bidding. However, these bidders probably assumed that Pacific Bell would fight hard for one of the licenses and that ALAACR would be the first to drop out of this competition.

Tampa in preparation for its round 98 bid in San Francisco. American Portable took the hint; it bid in round 98 for Houston and Tampa, ending the competition for the San Francisco licenses.¹⁸

One more pair of episodes deserves special mention if only because it is so hard to explain in the traditional mode of auction analysis. These are the jump bids made by ALAACR in its competition for the Los Angeles license in rounds 21 and 30. These bids, which raised Pacific Telesis's previous high bids by \$114 million and \$117 million, respectively, were two of the largest jump bids in the history of auctions. The first of these tripled the previous high bid, while the second increased the previous high bid by two-thirds. Yet neither of these bids seems to have been intended to win a license: in each case the ALAACR switched its attention at the very next opportunity to bid on the New York license. One can only infer that ALAACR did not wish to see the Los Angeles license sell cheaply compared to other licenses, although the reason for this goal cannot be inferred from its auction behavior.

Did all these clever stratagems benefit the bidders? The answer depends on counterfactuals. That is, it requires speculating about how a competitor would have behaved if a particular bidder had not adopted a particular stratagem. That is not something we can know. Nevertheless, we must suspect that the bidders who adopted the stratagems we described are feeling well satisfied. Wireless and GTE did, by their strategies, protect themselves from some dangers that they had apparently perceived. And

¹⁸A curious coda to this episode occurred at round 109, when Wireless renewed its bidding on the Houston license. This appears to have been part of an attempt to swap the Houston and Milwaukee licenses. American Portable apparently read the signal differently. It seems to have believed that Wireless had reneged on the (implicit) San Francisco deal. It responded by withdrawing enough of its own leading bids to acquire eligibility to renew bidding in San Francisco. Wireless avoided a fight by withdrawing its Houston bid, thereby reestablishing the terms of the earlier swap.

American Portable wound up acquiring major market licenses, despite its previous status as a niche player. From their likely perspectives, their bidding strategies could be judged successful.

To the professors who participated in the auction design and bidding, the spectrum auction outcome was a triumph. With their help, the FCC had avoided the pitfalls that had embarrassed governments in New Zealand and Australia and implemented a highly innovative design that encouraged straightforward bidding and promoted greater efficiency in the license assignments. With advice from their consultants, national bidders were mostly able to protect themselves from predatory bidding strategies and to assemble economically sensible collections of licenses. The Treasury received a substantial revenue increment, minority bidder participation was supported, and the auctions ran smoothly. With the extremely short timetable that Congress had imposed on the FCC to prepare for the auction, the past history of failures of government-run auctions, and the variety of environments in which the auction was run, its success testifies powerfully to the soundness of the spectrum auction design.

Still, as we shall see in the more theoretical chapters, the design that was adopted is far from the theoretical ideal. There is now an opportunity to develop auction theory in directions that identify the advantages of more sophisticated auction designs, the environments in which they are most likely to be add substantial value, and the kinds of modest auction design features that can be implemented when the advantages of sophistication are small. The remaining chapters, which analyze auctions from the perspectives of both buyers and sellers, aim to make a beginning, answering concrete questions about bidding and auction design.