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Spectrum Auctions

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Abstract

Auctions have emerged as the primary means of assigning spectrum licenses to companies wishing to provide wireless communication services. Since July 1994, the Federal Communications Commission (FCC) has conducted 33 spectrum auctions, assigning thousands of licenses to hundreds of firms. Countries throughout the world are conducting similar auctions. I review the current state of spectrum auctions. Both the design and performance of these auctions are addressed.

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From July 1994 to February 2001, the Federal Communications Commission (FCC) conducted 33 spectrum auctions, raising over $40 billion for the U.S. Treasury. The auctions assigned thousands of licenses to hundreds of firms. These firms are now in the process of creating the next generation of wireless communication services. The FCC is not alone. Countries throughout the world now are using auctions to assign spectrum. Indeed, the early auctions in Europe for third-generation (3G) mobile wireless licenses raised nearly $100 billion. Auctions have become the preferred method of assigning spectrum.

The FCC auctions have shown that using an auction to allocate scarce resources is far superior to the prior methods: comparative hearings and lotteries. With a well-designed auction, there is a strong tendency for the licenses to go to the parties that value them the most, and the Treasury obtains much-needed revenues in the process.

Overall, the auctions have been a tremendous success, putting essential spectrum in the hands of those best able to use it. The auctions have fostered innovation and competition in wireless communication services. Taxpayers, companies, and especially consumers have benefited from the auctions. In comparison with other countries, the FCC auctions represent the state-of-the-art in spectrum auction design and implementation. The FCC began its auctions with an innovative design, and has continued to improve the auctions since then. The FCC's leadership in spectrum auctions has had positive consequences worldwide. Many countries wisely have imitated the FCC auctions; those that have not have suffered from inefficient license assignments and other flaws.

All but two of the FCC auctions have used a simultaneous ascending design in which groups of related licenses are auctioned simultaneously over many rounds of bidding. In each round, bidders submit new higher bids on any of the licenses they desire, bumping the standing high bidder. The auction ends when a round passes without any bidding; that is, no bidder is willing to raise the price on any license. This design is a natural extension of the English auction to multiple related goods. Its advantage over a sequence of English auctions is that it gives the bidders more flexibility in moving among licenses as prices change. As one license gets bid up, a bidder can shift to an alternative that represents a better value. In this way, bidders are able to arbitrage across substitutable licenses. Moreover, they can build packages of complementary licenses using the information revealed in the process of bidding.

There is now substantial evidence that this auction design has been successful. Revenues often have exceeded industry and government estimates. The simultaneous ascending auction may be partially responsible for the large revenues. By revealing information in the auction process, bidder uncertainty is reduced, and the bidders safely can bid more aggressively. Also, revenues may increase to the extent the design enables bidders to piece together more efficient packages of licenses.

Despite the general success, the FCC auctions have experienced a few problems from which one can draw important lessons. One basic problem is the simultaneous ascending auction's vulnerability to revenue-reducing strategies in situations where competition is weak. Bidders have an incentive to reduce their demands in order to keep prices low, and to use bid signaling strategies to coordinate on a split of the licenses. I identify problems with the FCC and other spectrum auctions, and discuss how to minimize these problems.

I begin by explaining why it makes sense to auction the spectrum. Then I discuss auction design. The simultaneous ascending auction is discussed in detail, and its performance is evaluated. I describe how the auction format has evolved in response to perceived problems. The FCC's recently proposed approach to package bidding is discussed. I examine the UMTS auctions in Europe. Finally, I provide advice to governments engaged in spectrum auctions.

1 Why auction the spectrum?

There is substantial agreement among economists that auctions are the best way to assign scarce spectrum resources (McMillan 1995). Auctions ask an answer to the basic question 'Who should get the licenses and at what prices?' Ronald Coase (1959) proposed auctioning spectrum over forty years ago, yet it was not until 1994 that spectrum auctions became a reality in the US. Hazlett (1998) provides an analysis of the history that ultimately led to spectrum auctions.

Alternatives to auctions are an administrative process or lotteries. Both alternatives were used and then rejected in the US.

An administrative process has those that are interested in the spectrum make a proposal for how they intend to use it. This approach commonly is referred to as a "beauty contest." After hearing all the proposals, the regulator awards spectrum to those with the most attractive proposals. Beauty contests suffer from several problems. First, they are extremely slow and wasteful. Even with streamlined hearings, it took the FCC an average of two years to award thirty cellular licenses. Competitors spend vast sums trying to influence the regulator's decision. Second, beauty contests lack transparency. It is difficult

to see why one proposal won out over another. Worse yet, the ability of the regulator to successfully identify the best proposals is limited.

Unacceptable delays in assigning cellular licenses led the FCC to switch to lotteries. With a lottery, the FCC randomly selects license winners from among those that apply. The problem here is that since the licenses are enormously valuable there is a strong incentive for large numbers to apply. Indeed, the FCC received over four hundred thousand applications for its cellular lotteries. The huge number of applications wasted resources in creating and processing the applications. Moreover, the winners were not those best suited to provide a service. It took years for the licenses to be transferred via private market transactions to those capable of building out a service. Lotteries were quickly abandoned in favor of auctions.

The primary advantage of an auction is its tendency to assign the spectrum to those best able to use it. This is accomplished by competition among license applicants. Those companies with the highest value for the spectrum likely are willing to bid higher than the others, and hence tend to win the licenses. There are several subtleties, which are addressed below that limit the efficiency of spectrum auctions. Still a well-designed auction is apt to be highly efficient. A second important advantage of auctions is that the competition is not wasteful. The competition leads to auction revenues, which can be used to offset distortionary taxation. Finally, an auction is a transparent means of assigning licenses. All parties can see who won the auction and why.

Despite their virtues, standard auctions at best ensure that the bidder with the highest private value wins, rather than the bidder with the highest social value. Private and social values can diverge in these auctions because the winners will be competing in a marketplace. One collection of winners may lead to a more collusive industry structure. For example, a license may be worth more to an incumbent than a new entrant, simply because of the greater market power the incumbent would enjoy without the new entrant. Recognizing this, the regulator typically limits the amount of spectrum any one firm can hold in any geographic area.

2 Auction design

Spectrum auctions typically involve the sale of multiple interrelated licenses. We have only begun to understand such auctions in theory and practice. We neither have strong theoretical nor empirical results to guide the design of spectrum auctions. Designing spectrum auctions is as much art as it is science.

The objective of most spectrum auctions is two-fold. The primary goal is efficiency—getting the spectrum in the hands of those best able to use it. A secondary goal is revenue maximization. Even

efficiency-minded governments should care about the revenues raised at auction, since auction revenues are less distortionary than the principal source of government revenues—taxation. Economists estimate that the welfare loss from increasing taxes in the United States is in the range of 17–56 cents per dollar of extra revenue raised (Ballard et al. 1985). Hence, in designing the auction, the government should care about revenues. Another common objective is increasing competition for wireless services.

Sometimes it is argued that efficiency is not an important objective. If resale is allowed, will not postauction transactions fix any assignment inefficiencies? The answer is "yes" in a Coasean world without transaction costs. However, transaction costs are not zero. Postauction transactions often are made difficult by strategic behavior between parties with private information and market power. Efficient auctions are possible before assignments are made but may become impossible after an initial assignment. The problem is that the license holder exercises its substantial market power in the resale of the license (Cramton et al. 1987). For this reason, it is important to get the assignment right the first time. Moreover, efficient auctions tend to raise substantial revenues, especially when resale is possible (Ausubel and Cramton 1999).

Much of the research on spectrum auction design has focused on the Personal Communication Services (PCS) auctions in the US. Below I summarize several of the important issues, and the FCC's ultimate conclusion. These issues are discussed in several papers (e.g., Cramton 1997, McMillan 1994, Milgrom 2000, and Chakravorti et al. 1997, Krishna and Rosenthal 1997, Rosenthal and Wang 1997).

2.1 Open bidding is better than a single sealed bid

An essential advantage of open bidding is that the bidding process reveals information about valuations. This information promotes the efficient assignment of licenses, since bidders can condition their bids on more information. Moreover, to the extent that bidder values are affiliated, it may raise auction revenues (Milgrom and Weber 1982), since the winner's curse is reduced. Bidders are able to bid more aggressively in an open auction, since they have better information about the item's value.

The advantage of a sealed-bid design is that it is less susceptible to collusion (Milgrom 1987). Open bidding allows bidders to signal through their bids and establish tacit agreements. With open bidding, these tacit agreements can be enforced, since a bidder can immediately punish another that has deviated from the collusive agreement. Signaling and punishments are not possible with a single sealed bid.

A second advantage of sealed bidding is that it may yield higher revenues when there are ex ante differences among the bidders (Maskin and Riley 1995, Klemperer 1998). This is especially the case if the bidders are risk averse (Maskin and Riley 1984, Matthews 1983). In a sealed bid auction, a strong

bidder can guarantee victory only by placing a very high bid. In an open auction, the strong bidder never needs to bid higher than the second-highest value.

In the PCS spectrum auctions, there was a consensus among experts in favor of open bidding. The advantage of revealing more information in the bidding process was thought to outweigh any increased risk of collusion. Collusion was viewed as unlikely, and revenue maximization was a secondary goal.

2.2 Simultaneous open bidding is better than sequential auctions

A frequent source of debate was whether licenses should be sold in sequence or simultaneously. A disadvantage of sequential auctions is that they limit information available to bidders and limit how the bidders can respond to information. With sequential auctions, bidders must guess what prices will be in future auctions when determining bids in the current auction. Incorrect guesses may result in an inefficient assignment when license values are interdependent. A sequential auction also eliminates many strategies. A bidder cannot switch back to an earlier license if prices go too high in a later auction. Bidders are likely to regret having purchased early at high prices, or not having purchased early at low prices. The guesswork about future auction outcomes makes strategies in sequential auctions complex, and the outcomes less efficient.

In a simultaneous auction, a large collection of related licenses is up for auction at the same time. Hence, the bidders get information about prices on all the licenses as the auction proceeds. Bidders can switch among licenses based on this information. Hence, there is less of a need to anticipate where prices are likely to go. Moreover, the auction generates market prices. Similar items sell for similar prices. Bidders do not regret having bought too early or too late.

The Swiss wireless-local-loop auction conducted in March 2000 illustrates the difficulties of sequential sale. Three nationwide licenses were sold in a sequence of ascending auctions. The first two licenses were for a 28 MHz block; the third was twice as big (56 MHz). Interestingly, the first license sold for 121 million francs, the second for 134 million francs, and the third (the large license) sold for 55 million francs. The largest license sold for just a fraction of the prices of the earlier licenses.

Proponents of sequential auctions argue that the relevant information for the bidders is the final prices and assignments. They argue that simultaneous auctions do not reveal final outcomes until the auction is over. In contrast, the sequential auction gives final information about prices and assignments for all prior auctions. This final information may be more useful to bidders than the preliminary information revealed in a simultaneous auction.

Supporters of sequential auctions also point out that the great flexibility of a simultaneous auction makes it more susceptible to collusive strategies. Since nothing is assigned until the end in a simultaneous auction, bidders can punish aggressive bidding by raising the bids on those licenses desired by the aggressive bidder. In a sequential auction, collusion is more difficult. A bidder that is supposed to win a later license at a low price is vulnerable to competition from another that won an earlier license at a low price. The early winner no longer has an incentive to hold back in the later auctions.

In the end, the decision makers at the FCC were convinced that the virtues of the simultaneous auction—greater information release and greater bidder flexibility in responding to information—would improve efficiency. Although the FCC was concerned that a simultaneous auction might be more collusive, it felt that the setting was otherwise not conducive to collusion. In any event, sequential auctions would not eliminate the possibility for collusion.

The ability to successfully implement a novel auction form was a chief concern. However, the FCC was able to test and refine the simultaneous auction in the simpler and lower stake setting of narrowband licenses. In addition, experimental tests of the design were conducted before the first narrowband auction began. Tests were conducted at CalTech's experimental lab by Charles Plott, David Porter, and John Ledyard. Several large bidders conducted their own tests as well. These tests provided evidence that the design would work in practice.

2.3 Package bids are too complex

A bidder's value of a license may depend on what other licenses it wins. Philadelphia may be worth more to a bidder if it wins the adjacent licenses in New York and Washington. Hence, bidders may value being able to bid on a combination of licenses, rather than having to place a number of individual bids. With a package bid, the bidder either gets the entire combination or nothing. There is no possibility that the bidder will end up winning just some of what it needs.

With individual bids, bidding for a synergistic combination is risky. The bidder may fail to acquire key pieces of the desired combination, but pay prices based on the synergistic gain. Alternatively, the bidder may be forced to bid beyond its valuation in order to secure the synergies and reduce its loss from being stuck with the dogs. This is the exposure problem. Individual bidding exposes bidders seeking synergistic combinations to aggregation risk.

Not allowing package bids can create inefficiencies. For example, suppose there are two bidders for two adjacent parking spaces. One bidder with a car and a trailer requires both spaces. She values the two spots together at $100 and a single spot is worth nothing; the spots are perfect complements. The second

bidder has a car, but no trailer. Either spot is worth $75, as is the combination; the spots are perfect substitutes. Note that the efficient outcome is for the first bidder to get both spots for a social gain of $100, rather than $75 if the second bidder gets a spot. Yet any attempt by the first bidder to win the spaces is foolhardy. The first bidder would have to pay at least $150 for the spaces, since the second bidder will bid up to $75 for either one. Alternatively, if the first bidder drops out early, she will "win" one license, losing an amount equal to her highest bid. The only equilibrium is for the second bidder to win a single spot by placing the minimum bid. The outcome is inefficient, and fails to generate revenue. In contrast if package bids are allowed, then the outcome is efficient. The first bidder wins both licenses with a bid of $75 for both spots.

This example is extreme to illustrate the exposure problem. The inefficiency involves large bidder-specific complementarities and a lack of competition. In the PCS auctions and most other spectrum auctions, the complementarities are less extreme and the competition is greater.

Unfortunately, allowing package bids creates other problems. Package bids may favor bidders seeking large aggregations due to a variant of the free-rider problem, called the threshold problem (Bykowsky, et al. 2000, Milgrom 2000). Continuing with the last example, suppose that there is a third bidder who values either spot at $40. Then the efficient outcome is for the individual bidders to win both spots for a social gain of 75 + 40 = $115. But this outcome may not occur when values are privately known. Suppose that the second and third bidders have placed individual bids of $35 on the two licenses, but these bids are topped by a package bid of $90 from the first bidder. Each bidder hopes that the other will bid higher to top the package bid. The second bidder has an incentive to understate his willingness to push the bidding higher. He may refrain from bidding, counting on the third bidder to break the threshold of $90. Since the third bidder cannot come through, the auction ends with the first bidder winning both spaces for $90.

A second problem with allowing package bids is complexity. If all combinations are allowed, even identifying the revenue maximizing assignment is an intractable integer programming problem when there are many bidders and licenses. The problem can be made tractable by restricting the set of allowable combinations (Rothkopf, et al. 1998). However, these restrictions may eliminate many desirable combinations, especially in broadband PCS where cellular holdings and other existing infrastructure tend to create idiosyncratic license synergies. Alternatively, a bid mechanism can be used that puts the computational burden on the bidders. In the AUSM system, bidders must propose bids that in combination with other bids exceed the amount bid for standing package bids (Banks, et al. 1989).

Increased complexity is a legitimate concern when considering package bids. Although simultaneous auctions with package bids were successfully used in the laboratory (Bykowsky, et al. 2000), it was far from certain that the FCC could successfully run auctions with package bids under the tight time schedule in the early auctions.

The FCC decided against allowing package bids in its early auctions. The threshold problem and increased complexity of package bids were thought to be worse than the exposure problem. However, since the initial PCS auctions, the FCC has done further research on package bidding, and intends to use it in the 700 MHz auction as discussed below.

2.4 Other issues

Having settled on a simultaneous ascending auction without package bids, several issues of implementation remained.

How much information should the bidders be given? The insights from Milgrom and Weber (1982) suggest that typically more public information is better. Hence, with the exception of bidder identities in the nationwide auction, the FCC decided to reveal all information: the identities of the bidders, all the bids, and the bidders' current eligibility. So long as collusion and predatory bidding are not problems, revealing more information should improve efficiency and increase revenues. It also makes for a more open process.

Should the rounds be discrete or continuous? The FCC decided on discrete rounds, which would give the bidders a specific amount of time to respond to bids. Continuous bidding has the advantage that it makes endogenous the time between bids. Bidders can respond quickly when the strategic situation is simple, and take more time when it is complex. Discrete bidding is easier to implement and it gives the bidders a specific schedule to follow. Bidders know exactly when new information will be available and when they have to respond.

How can the FCC best control the pace of the auction? There are three key instruments: the frequency of rounds, the minimum bid increments, and an activity rule, which sets minimum levels of bidding activity. These are discussed later.

3 Simultaneous ascending auction

The simultaneous ascending auction has emerged as the standard approach to spectrum auctions. This design has been successfully used and refined by the FCC in over two-dozen auctions. Other

countries, such as Australia, Canada, Mexico, the Netherlands, and the United Kingdom, have used this design as well. Below is a description of the rules for a generic FCC auction.

The simultaneous ascending auction works as follows. A group of licenses with strong value interdependencies are up for auction at one time. A bidder can bid on any collection of licenses in any round, subject to an activity rule which determines the bidder's current eligibility. The auction ends when a round passes with no new bids on any license. This auction form was thought to give the bidders flexibility in expressing values and building license aggregations. An auction winner gains the exclusive right to use the spectrum in accordance with FCC rules for a period of ten years. Licenses typically are renewed with a negligible charge provided the licensee has adhered to FCC rules and met buildout requirements. Licensees at any time may resell licenses purchased without special preference. Resale of licenses purchased with special preference is restricted to prevent “unjust enrichment.”

Spectrum Cap. To promote competition, a firm is limited in the quantity of spectrum it can hold in any market. For example in US auctions, firms can hold no more than 45 MHz of broadband spectrum in any area, assuring that there are at least five broadband wireless competitors in each market.

Payment Rules. Payments are received by the FCC at three times: (1) An upfront payment before the bidding begins assures that the bidder is serious. Any withdrawal or default penalties are taken from the bidder's upfront payment. (2) A down payment of 20 percent is paid within five business days after the close of the auction. (3) A final payment of the remaining 80 percent is paid within five business days of the award of the license. Licenses are awarded one to three months after the auction.

The upfront payment is a refundable deposit. It is due two weeks before the auction begins and defines the bidder's maximum eligibility in any round of bidding. A bidder interested in winning a large quantity of licenses would have to submit a large upfront payment; a bidder with more limited interests could submit a smaller upfront payment. The size of a license typically is measured in MHz-pop: the bandwidth in megahertz times the population in the license area. In early PCS auctions, each bidder made an upfront payment of $.02 per MHz-pop for the largest combination of licenses the bidder intended to be active on in any round. A bidder is active on a license if it places a new bid in the round or was the high bidder on the license in the prior round. Thus, an upfront payment of $6 million in the AB broadband PCS auction would make a bidder eligible to be active on 30 MHz licenses covering $6/(30\times.02) = 10$ million people. The upfront payment is not license specific; it simply limits total bidding activity in any round.

Designated Entities. To encourage broad participation in wireless communications, designated firms (women, minorities, and/or small businesses) were given bidding credits on specific licenses. These credits, ranging from 10% to 40%, were intended to offset any disadvantage these firms faced in raising

capital and providing services. Some auctions also gave designated entities favorable installment payments terms. These were later abandoned.

Minimum Bid Increments. To assure that the auction concludes in a reasonable amount of time, the FCC specifies minimum bid increments between rounds. Bid increments are set at the greater of a percentage increment and an absolute increment. Bid increments are adjusted in response to bidder behavior. In the early rounds, when bid activity is high, the FCC sets larger bid increments; in the later rounds, when bid activity is low, the FCC sets smaller bid increments. Typically, the bid increments are between 5 and 20 percent.

Activity Rule. The activity rule, proposed by Paul Milgrom and Robert Wilson, is a further device for controlling the pace of the auction. It forces a bidder to maintain a minimum level of activity to preserve its current eligibility. As the auction progresses, the activity requirement increases in stages. For example, the activity requirement might be 60% in stage 1, 80% in stage 2, and 100% in stage 3 (the final stage). With a 60% activity requirement, each bidder must be active on a quantity of licenses, measured in MHz-pop, equal to at least 60% of the bidder's current eligibility. If activity falls below the 60% level, then the bidder's current eligibility is reduced to its current activity divided by 60%. With a 100% activity requirement, the bidder must be active on 100% of its current eligibility or its eligibility drops to its current activity. The lower activity requirement early in the auction gives the bidder greater flexibility in shifting among license aggregations early on when there is the most uncertainty about what will be obtainable.

A waiver prevents a reduction in eligibility in the event of bidder error or some other problem. Bidders typically are given five waivers. Waivers are applied automatically. An automatic waiver is used whenever a bidder's eligibility would otherwise fall as a result of its reduced bid activity. A bidder that does not wish to maintain its eligibility from the prior round may override the automatic waiver.

Number of Rounds per Day. A final means of controlling the pace of the auction is the number of rounds per day. Typically, fewer rounds per day are conducted early in the auction when the most learning occurs. In the later rounds, there is much less bidding activity, and the rounds can occur more quickly. The FCC has conducted as few as one round per day and as many as twenty per day.

Stopping Rule. A simultaneous stopping rule is used to give the bidders maximum flexibility in pursuing backup strategies. All markets close if a single round passes in which no new bids are submitted on any license, and the auction is in its final stage.

Bid Information. Each bidder is fully informed about the identities of the bidders, the size of the upfront payments, and which bidders qualify as designated entities. High bids and bidder identities are posted after each round. In addition, all bids and bidder identities are displayed at the conclusion of each round, together with each bidder's eligibility and waivers.

Bid Withdrawal. The high bidders can withdraw their bids subject to a bid withdrawal penalty. If a bidder withdraws its high bid, the FCC is listed as the high bidder and the minimum bid is the second-highest bid for that license. The second-highest bidder is in no way responsible for the bid, since this bidder may have moved on to other properties. If no firm bids on the license, the FCC can reduce the minimum bid. Typically, the FCC drops the minimum bid at most once, before committing not to reduce the minimum bid further.

To discourage insincere bidding, there are penalties for withdrawing a high bid. The penalty is the larger of 0 and the difference between the withdrawn bid and the final sale price. This penalty is consistent with the standard remedy for breach of contract. The penalty equals the damage suffered by the FCC as a result of the withdrawal. If the bidder defaults or is disqualified after the close of the auction, the penalty is increased by 3% of the eventual sale price to compensate the FCC for additional selling costs. The additional 3% default payment is also intended to discourage defaults (after the auction closes) relative to withdrawals (during an auction).

4 Performance of the simultaneous ascending auction

Since we do not observe the values firms place on licenses, it is impossible to directly assess the efficiency of the simultaneous ascending auction. Nonetheless, we can indirectly evaluate the auction design from the observed behavior (Cramton 1998, McAfee and McMillan 1996). I focus especially on the three PCS broadband auctions, which I refer to as the AB auction, the C auction, and the DEF auction, indicating the block(s) of spectrum that were assigned in each.

Revenue is a first sign of success. Auction revenues have been substantial. Revenues in US auctions typically have exceeded industry and government estimates. The simultaneous ascending auction may be partially responsible for the large revenues. By revealing information in the auction process, the winner's curse is reduced, and the bidders can bid more aggressively. Also, revenues may increase to the extent the design enables bidders to piece together more efficient packages of licenses.

A second indicator of success is that the auctions tended to generate market prices. Similar items sold for similar prices. In the narrowband auctions, the price differences among similar licenses were at

most a few percent and often zero. In the first broadband auction, where two licenses were sold in each market, the prices differed by less than one minimum bid increment in 42 of the 48 markets.

A third indicator of success is the formation of efficient license aggregations. Bidders did appear to piece together sensible license aggregations. This is clearest in the narrowband auctions. In the nationwide narrowband auction, bidders buying multiple bands preferred adjacent bands. The adjacency means that the buffer between bands can be used for transmission, thus increasing capacity. The two bidders that won multiple licenses were successful in buying adjacent bands. In the regional narrowband auction, the aggregation problem was more complicated. Several bidders had nationwide interests, and these bidders would have to piece together a license in each of the five regions, preferably all on the same band, in order to achieve a nationwide market. The bidders were remarkably successful in achieving these aggregations. Four of the six bands sold as nationwide aggregations. Bidders were able to win all five regions within the same band. Even in the two bands that were not sold as nationwide aggregations, bidders winning multiple licenses won geographically adjacent licenses within the same band.

Large aggregations were also formed in the PCS broadband auctions. Bidders tended to win the same band when acquiring adjacent licenses. In the AB auction, the three bidders with nationwide interests appeared to have efficient geographic coverage when one includes their cellular holdings. The footprints of smaller bidders also seem consistent with the bidders' existing infrastructures. In the C-block auction, bidders were able to piece together contiguous footprints, although many bidders were interested in stand-alone markets.

Ausubel et al. (1997) and Moreton and Spiller (1998) analyze the AB and C auction data to see if there is evidence of local synergies. Consistent with local synergies, these studies find that bidders did pay more when competing with a bidder holding neighboring licenses. Hence, bidders did bid for synergistic gains and, judging by the final footprints, often obtained them.

The two essential features of the FCC auction design are (1) the use of multiple rounds, rather than a single sealed bid, and (2) simultaneous, rather than sequential sales. The goal of both of these features is to reveal information and then give the bidders the flexibility to respond to the information. There is substantial evidence that the auction was successful in revealing extensive information. Bidders had good information about both prices and assignments at a point in the auction where they had the flexibility to act on the information (Cramton 1997). The probability that a high bidder would eventually win the market was high at the midpoint of each auction. Also the correlation between mid-auction and final prices was high in each auction. Information about prices and assignments improved throughout each auction and was of high quality before bidders lost the flexibility to move to alternative packages.

The absence of resale also suggests that the auctions were highly efficient. In the first two years of the PCS auctions, there was little resale. GTE was the one exception. Shortly after the AB auction ended, GTE sold its AB winnings for about what it paid for the licenses. Apparently there was a shift in corporate strategy away from PCS and toward cellular.

5 Demand reduction and collusive bidding

Despite the apparent success of these auctions, an important issue limiting both efficiency and revenues is demand reduction and collusive bidding. This issue stems from the fact that these are multiple-item auctions. The efficiency results from single-item auctions do not carry forward to the multiple-item setting. In an ascending auction for a single item, each bidder has a dominant strategy of bidding up to its private valuation. Hence, the item always goes to the bidder with the highest value. If, instead, two identical items are being sold in a simultaneous ascending auction, then a bidder has an incentive to stop bidding for the second item before its marginal valuation is reached. Continuing to bid for two items raises the price paid for the first. As a result, the bidder with the highest value for the second item may be outbid by a bidder demanding just a single unit.

This logic is quite general. In multi-unit uniform-price auctions, typically every equilibrium is inefficient (Ausubel and Cramton 1996). Bidders have an incentive to shade their bids for multiple units, and the incentive to shade increases with the quantity being demanded. Hence, large bidders will shade more than small bidders. This differential shading creates an inefficiency. The small bidders will tend to inefficiently win licenses that should be won by the large bidders. The intuition for this result is analogous to why a monopolist's marginal revenue curve lies below its demand curve: bringing more items to market reduces the price received on all items. In the auction, demanding more items raises the price paid on all items. Hence, the incentive to reduce demand.

The FCC spectrum auctions can be viewed as an ascending-bid version of a uniform-price auction. Certainly, for licenses that are close substitutes, the simultaneous ascending auction has generated near uniform prices for similar items. However, the incentives for demand reduction and collusive bidding likely are more pronounced in an ascending version of the uniform-price auction (Cramton and Schwartz 1999, Ausubel and Schwartz 1999).[1] To illustrate this, consider a simple example with two identical goods and two risk-neutral bidders. Suppose that to each bidder the marginal value of winning one item is the same as the marginal value of winning a second item. These values are assumed independent and private, with each bidder drawing its marginal value from a uniform distribution on [0, 100]. First

[1] But see Perry and Reny (1999) that construct an efficient equilibrium in the simultaneous ascending auction.

consider the sealed-bid uniform price auction where each bidder privately submits two bids and the highest two bids secure units at a per-unit charge equal to the third highest bid. There are two equilibria to this sealed-bid auction: a demand-reducing equilibrium where each bidder submits one bid for $0 and one bid equal to its marginal value; and a sincere equilibrium where each bidder submits two bids equal to its marginal value. The sincere equilibrium is fully efficient in that both units will be awarded to the bidder who values them more. The demand-reducing equilibrium, however, raises zero revenue (the third-highest bid is zero) and is inefficient since the bidder with the higher value wins only one unit.

Next consider the same setting, but where an ascending version of the auction is used. Specifically, view the ascending auction as a two-button auction where there is a price clock that starting from price 0 increases continuously to 100. The bidders depress the buttons to indicate the quantity they are bidding for at every instant. The buttons are "non-repushable" meaning a bidder can decrease its demand but cannot increase its demand. Each bidder observes the price and can observe how many buttons are being depressed by its opponent. The auction ends at the first price such that the total number of buttons depressed is less than or equal to two. This price is called the stop-out price. Each bidder will win the number of units she demands when the auction ends, and is charged the stop-out price for each unit she wins. In this game, if weakly dominated strategies are eliminated, there is a unique equilibrium in which the bidding ends at a price of zero, with both bidders demanding just a single unit. The reason is that each bidder knows that if it unilaterally decreases its bidding to one unit, the other bidder will instantaneously end the auction, as argued above. But since the bidder prefers the payoff from winning one unit at the low price over its expected payoff of winning two units at the price high enough to eliminate the other bidder from the auction, the bidder will immediately bid for just one unit, inducing an *immediate* end to the auction. Thus, the only equilibrium here is analogous to the demand-reducing equilibrium in the sealed-bid uniform-price auction. The efficient equilibrium does not obtain. This example shows that the incentives to reduce demand can be more pronounced in an open auction, where bidders have the opportunity to respond to the elapsed bidding. The 1999 German GSM spectrum auction, which lasted just two rounds, illustrates this behavior (Jehiel and Moldovanu 2000).

This example is meant to illustrate that in simple settings with few goods and few bidders, bidders have the incentive to reduce demand. Direct evidence of demand reduction was seen in the nationwide narrowband auction. The largest bidder, PageNet, reduced its demand from three of the large licenses to two, at a point when prices were still well below its marginal valuation for the third unit (Cramton 1995). PageNet felt that, if it continued to demand a third license, it would drive up the prices on all the others to disadvantageously high levels.

An examination of the bidding in the AB auction is suggestive that the largest bidders did drop out of certain markets at prices well below plausible values, as a result of either demand reduction or tacit collusion.

Further evidence of demand reduction comes from the C auction. One large bidder defaulted on the down payment, so the FCC reauctioned the licenses. Interestingly, the licenses sold for 3 percent more than in the original auction. Consistent with demand reduction, NextWave, the largest winner in the C auction, bought 60 percent of the reauctioned spectrum. This occurred despite the fact that NextWave was not the second-highest bidder on any of these licenses in the original auction. NextWave was able to bid aggressively in the reauction, knowing that its bidding would have no affect on prices in the original auction.

Engelbrecht-Wiggans and Kahn (1999) and Brusco and Lopomo (1999) show that for an auction format like the FCC's, where the bidding occurs in rounds and bidding can be done on distinct units, that there exist equilibria where bidders coordinate a division of the available units at low prices relative to own values. Bidders achieve these low-revenue equilibria by threatening to punish those bidders who deviate from the cooperative division of the units. The idea in these papers is that bidders have the incentives to split up the available units ending the auction at low prices. With heterogeneous goods and asymmetric bidders in terms of budgets, capacities, and current holdings of complementary goods, it is unlikely that bidders would be aware of a simple equilibrium strategy that indicates which licenses to bid on and which to avoid. However, bidders in the FCC auctions, especially the DEF auction, took advantage of signaling opportunities to coordinate how to assign the licenses. With signaling, bidders could indicate which licenses they most wanted and which licenses they would be willing to forgo. Often this communication took the form of punishments.

Cramton and Schwartz (1999) examine collusive bidding strategies in the DEF auction. During the DEF auction the FCC and the Department of Justice observed that some bidders used bid signaling to coordinate the assignment of licenses. Specifically, some bidders engaged in *code bidding*. A code bid uses the trailing digits of the bid to tell other bidders on which licenses to bid or not bid. Since bids were often in millions of dollars, yet were specified in dollars, bidders at negligible cost could use the last three digits—the trailing digits—to specify a market number. Often, a bidder (the sender) would use these code bids as retaliation against another bidder (the receiver) who was bidding on a license desired by the sender. The sender would raise the price on some market the receiver wanted, and use the trailing digits to tell the receiver on which license to cease bidding. Although the trailing digits are useful in making clear which market the receiver is to avoid, *retaliating bids* without the trailing digits can also send a clear

message. The concern of the FCC is that this type of coordination may be collusive and may dampen revenues or efficiency.

The DEF auction was especially vulnerable to collusive bidding, it featured both small markets and light competition. Small markets enhanced the scope for splitting up the licenses. Light competition increased the possibility that collusive bidding strategies would be successful. Indeed, prices in the DEF auction were much lower than prices in the two earlier broadband PCS auctions.

From a strategic viewpoint, the simultaneous ascending auction can be thought of as a negotiation among the bidders. The bidders are negotiating how to split up the licenses among themselves, but only can use their bids for communication. The auction ends when the bidders agree on the division of the licenses. Retaliating bids and code bids are strategies to coordinate on a split of the licenses at low prices. In addition, bidders with a reputation for retaliation may scare off potential competitors. Cramton and Schwartz (CS) hypothesize that bidders who commonly use these strategies pay less for the spectrum they ultimately win.

CS find that six of the 153 bidders in the DEF auction regularly signaled using code bids or retaliating bids. These bidders won 476 of the 1,479 licenses for sale in the auction, or about 40% of the available spectrum in terms of population covered. Controlling for market characteristics, these signaling bidders paid significantly less for their licenses.

Further evidence that retaliation was effective in reducing prices is seen by the absence of arbitrage between the D and E blocks in each market. In particular, CS find that there was a tendency for bidders to avoid AT&T, a large bidder with a reputation for retaliation. If bidders did not care about the identity of the high bidder, they would arbitrage the prices of the D and E blocks, and bid against AT&T if the other block was more expensive. This did not happen. Even when the price of the other block was 50% higher, bidders bid on the higher priced block 27% of the time, rather than bid against AT&T.

Following the experience in the DEF auction, the FCC restricted bids to a whole number of bid increments (typically between 1 and 9) above the standing high bid. This eliminates code bidding, but it does nothing to prevent retaliating bids. Retaliating bids may be just as effective as code bids in signaling a split of the licenses, when competition is weak.

The auctioneer has many instruments to reduce the effectiveness of bid signaling. These include:

- Concealing bidder identities. This prevents the use of targeted punishments against rivals. Unless there are strong efficiency reasons for revealing identities, anonymous auctions may be preferable.

- Setting high reserve prices. High reserve prices reduce the incentive for demand reduction in a multiple-item auction, since as the reserve price increases the benefit from reducing demands falls. Moreover, higher reserve prices reduce the number of rounds that the bidders have to coordinate a split of the licenses and still face low prices.

- Offering preferences for small businesses and non-incumbents. Competition is encouraged by favoring bidders that may otherwise be disadvantaged ex ante. In the DEF auction, competition for the D and E license could have been increased by extending small business preferences to the D and E blocks, rather than restricting the preferences to the F block.

- Offering larger licenses. Many small licenses are more easily split up. At the other extreme a single nationwide license is impossible to split up. In the absence of synergies, such extreme bundling may have negative efficiency consequences, but improve revenues.

In auctions for identical items, the inefficiencies of demand reduction can be eliminated with a Vickrey (1961) auction. Alternatively, one can use Ausubel's (1997) ascending implementation of the static Vickrey auction, which has the additional advantages of an ascending-bid design. However, most spectrum auctions are not for identical items, so Vickrey-type mechanisms often are not practical.

6 Lessons learned and auction enhancements

The FCC auction rules have evolved in response to the experience of more than two dozen auctions. An examination of this evolution is instructive. Despite many enhancements, the FCC spectrum auctions have retained the same basic structure, a strong indication of an excellent initial design. The intent of the changes were to reduce speculative bidding, to avoid collusion, and to speed the auction along.

Elimination of installment payments. A potentially serious inefficiency in the C auction was speculative bidding caused by overly attractive installment payment terms. Bidders only had to put down 5 percent of their bids at the end of the auction, a second 5 percent at the time of license award, and then quarterly installment payments at the 10-year Treasury rate with interest-only payments for the first 6 years. These attractive terms favor bidders that are speculating in spectrum. If prices go up, the speculators do well; if prices fall, the speculators can walk away from their down payments. Indeed, spectrum prices did fall after the C auction, and most of the large bidders in the C auction defaulted on the payments. As a result of this experience, the FCC no longer offers installment payments. Bids must be paid in full when the licenses are awarded.

Click-box bidding. Bidders in FCC auctions no longer enter bids in dollars. Rather, the bidder indicates in a click-box the number of bid increments from 1-9 that it wishes to bid above the standing

high bid. If the standing high bid is 100 and the minimum bid increment is 10%, then the allowable bids would be 110, 120, …, 190, corresponding to the allowable increment bids of 1, 2, …, 9. This approach solves two problems. First, it eliminates code bidding. Bidders can no longer use the trailing digits of bids to signal to other bidders who should win what. Second, it reduces the possibility of mistaken bids. There were several instances of bidders adding too many zeros to the end of their dollar bids. With click-box bidding, substantial jump bids are permitted but not gross mistakes.

The downside of click-box bidding is the greater possibility of tie bids. This turns out not to be a serious problem. Although ties do occur early in the auction, it is unlikely that the final bid on a license involves a tie. Still ties do occur, and so the FCC tie-breaking rule takes on greater importance. The FCC breaks ties with the time stamp. Bids entered earlier have preference. Since bidders often have a mild preference for being the standing high bidder, it is common for bidders to race to enter their bids early in the round to win ties. Such behavior is undesirable, and so the FCC is now considering a random tie-breaking rule in future auctions.

License-specific bid increments. In early auctions, the FCC used the same percentage increment for all licenses. This was fine for auctioning a handful of similar licenses. However, when auctioning hundreds of heterogeneous licenses, it was found that some licenses would have a lot of bidding activity and others would have little activity. To speed the auction along, it makes sense to use larger bid increments for more active licenses. In recent auctions, the FCC adjusts the bid increments for each license based on the license's history of bid activity, using an exponential smoothing formula. Percentage increments tend to range between 5 and 20 percent, depending on prior activity. More active licenses have a larger increment.

Limit the use of withdrawals. Bid withdrawals were introduced to permit bidders to back out of a failed aggregation. The DEF auction had 789 withdrawals. Few if any of these withdrawals were related to failed aggregations. Rather, most of the withdrawals appear to have been used as a strategic device, in one of two ways: (1) as a signal of the bidder's willingness to give up one license in exchange for another or (2) as part of a parking strategy to maintain eligibility without bidding seriously. This undesirable use of withdrawals was also observed in other auctions. As a result, the FCC now only allows withdrawals in at most two rounds of the auction for any bidder. This enables the bidder to back out of up to two failed aggregations, and yet prevents the frequent strategic use of withdrawals.

Combine bid submission and withdrawal phases. The FCC originally divided a round of bidding into two phases, a bidding phase followed by a withdrawal phase. The separation of these phases was largely a historical artifact and provides little benefit. Its main effect was to impede the pace of the auction.

The FCC has since combined the two phases into one. With the combined procedure, bid submission consists of two steps: withdrawal followed by submission. In the withdrawal step, the bidder may withdraw on any or all licenses on which it is the high bidder. Then, in the bid submission step, the bidder places any desired new bids, with available eligibility increased to reflect the withdrawals. Hence, a bidder withdrawing in New York can then place a bid (in the same round) on Los Angeles, because of the eligibility freed by the New York withdrawal.

Faster rounds. The FCC's auction system now permits much faster rounds than the initial implementation. In many auctions, bidding activity is slow in the later part of the auction. Hence, being able to conduct 20 or more rounds per day is important in speeding the auction along.

Minimum opening bids. Early FCC auctions did not use minimum opening bids; any opening bid greater than zero was acceptable. The FCC now sets substantial minimum opening bids. These bid limits both increase the pace and reduce the potential for collusion. By starting at a reasonably high level, the bidders have fewer rounds to resolve their conflicts at low prices. The benefit of collusive strategies is reduced.

7 Package bidding

One auction enhancement that has received considerable attention is package bidding. A key simplification of the FCC auctions is only allowing bids on individual licenses. This works well in settings where there are not large complementarities across licenses, or if there are large complementarities, then where the complementarities are similar among the bidders. In such a setting, the exposure problem is slight. There is little likelihood that a sincere bidder will get stuck with licenses it does not want. However, in auctions where license complementarities are large and differ among bidders, then the exposure problem may be substantial. In this latter case, allowing package bids—all-or-nothing bids on collections of complementary licenses—can reduce the exposure problem and improve efficiency. Efficiency can also be improved by reducing the incentives for demand reduction by large bidders.

Auctions with package bidding, often referred to as combinatorial auctions or package auctions, are actively being researched. In May 2000, the FCC sponsored a conference on the topic.[2] A goal of the conference was to determine the best way to introduce package bidding in the 700 MHz auction to take place in Fall 2000. The 700 MHz auction represented a good test-case for package bidding for two reasons. First, it is a relatively simple case, since it involves only 12 licenses: 2 bands (one 10 MHz and

[2] The conference materials are available at http://wireless.fcc.gov/auctions/31/. This site also includes the comments, reply comments, and FCC documents on package bidding.

one 20 MHz) in each of 6 regions. Second, perspective bidders had expressed interest in alternative packaging. Those bidders intending to provide a fixed high-speed data service desired the full 30 MHz in a particular region. Some mobile wireless providers desired individual licenses to add capacity in congested regions or to fill out their footprint. Still others desired nationwide packages to offer a nationwide mobile service.

The conference resulted in FCC Public Notice DA00-1075 seeking comment on modifying the simultaneous ascending auction to allow package bidding in the 700 MHz auction. After comments and reply comments were received, the FCC issued Public Notice DA00-1486 adopting and describing the package bidding rules for the 700 MHz auction. I briefly describe the approach taken by the FCC in this auction. The rules are intended to improve the efficiency of the auction by avoiding the exposure problem, while limiting the threshold problem.

A bidder can bid on the individual licenses as in the standard simultaneous ascending auction. In addition, a bidder can place all-or-nothing bids on up to twelve packages, which the bidder determines at any point in the auction. In this way the bidder can avoid the exposure problem when licenses are complements. The provisional winning bids are the set of consistent bids that maximize total revenues. Consistent bids are bids that (1) do not overlap, and (2) are made or renewed in the same round. Bids made by a bidder in different rounds are treated as mutually exclusive.[3]

Limiting each bidder to twelve bidder-specific packages simplifies the auction, and still gives the bidders great flexibility in expressing synergies for various license combinations. The FCC's original proposal allowed only nine package bids: the six 30 MHz regional bids, and three nationwide bids (10, 20, or 30 MHz). Although these nine packages were consistent with the expressed desires of many perspective bidders, others felt that the nine packages were too restrictive.

The activity rule is unchanged, aside from a new definition of activity and a lower activity requirement of 50%, giving the bidders greater flexibility in shifting among packages. A bidder must be active on 50% of its current eligibility or its eligibility in the next round will be reduced to two times its activity. A bid counts as activity if (1) it is part of a provisionally winning set in the prior round, or (2) it is a new bid or a renewal of a provisionally winning bid in the prior round. A bidder's activity level is the maximum number of bidding units a bidder can win considering only those licenses and packages on which the bidder is active. Bids made in different rounds are treated as mutually exclusive; hence, a

[3] This and several other features of the design were recommended by Paul Milgrom. See http://wireless.fcc.gov/auctions/31/.

bidder wishing to add a license or package to its provisional winnings must renew the provisional winning bids in the current round.

The FCC adopted a two-round simultaneous stopping rule. The auction ends after two consecutive rounds of no new bids on any licenses or packages. Renewed bids do not count as new bids. The two-round approach gives bidders fair warning that the auction may end if they do not place a new bid.

The determination of minimum bids is an important change in the rules, since it impacts the extent of the threshold problem faced by those bidding on individual licenses or small packages. The minimum bid on a license or package is the greater of: (1) the minimum opening bid, (2) the bidder's own previous high bid on that package plus x%, and (3) the number of bidding units of the package times the lowest $/bidding unit on any package in the last five rounds. The FCC specifies x, and retains discretion to adjust minimum bids on a license-by-license or package-by-package basis.

The key feature of this minimum bid rule is point (2), which makes the minimum bid depend on the bidder's prior high bid for the package. This recognizes that since a bidder's bids in different rounds are mutually exclusive, another bidder's bid on a package can be a provisionally winning bid even if it is less than the high bid of the prior round. Hence, the rules allow bids that are below another's prior high bid. Points (1) and (3) limit how low a bidder can bid when it starts out bidding on a new package. The bid must be at least as great as the minimum opening bid and the least expensive package on a per unit basis.

The FCC will continue to use "click box" bidding, in which the bidder specifies either the minimum bids or an integer between 1 and 9. A bid of 1 is the minimum bid plus x% of the minimum bid; a bid of 2 is the minimum bid plus 2x% of the minimum bid; and so on. The FCC considered limiting bids on packages to the minimum bid to reduce the threshold problem; however, it was felt that the revised minimum bid rule adequately addressed the threshold problem.

Another change is allowing bidders to submit "last and best" bids. Last and best bids can be for any amount between the bidder's prior high bid and the minimum bid. A bidder cannot bid again after placing one or more last and best bids.

A bidder can renew the highest bid it made on any license or package. Renewing a bid does not increase the bid amount. Renewed bids are needed, since bids in different rounds are treated as mutually exclusive. Thus, if a bidder wishes to win both its provisional winners from the prior round plus a new license, it must bid on the new license and renew the provisional winners. Activity credit is not given for renewing a bid that is not a provisional winner.

Provisional winning bids are the set of "consistent" bids (bids that do not overlap and are made or renewed by a bidder in the same round) that maximize revenues as of the current round. Winning bids are the provisional winning bids at the end of the auction. Ties are broken randomly. Licenses on which no bids have been submitted are treated as if the minimum opening bid was placed. This is consistent with the minimum opening bids reflecting the FCC's opportunity cost of selling the licenses.

Treating a bidder's bids in different rounds as mutually exclusive is an important feature. First, it gives bidders a vehicle for submitting contingent "or" bids. If the bidder desires one package or the other, but not both, the bidder simply bids for the two packages in separate rounds. Bidders can shift to backup strategies without fear that they will win a collection of licenses they do not desire. Second, it encourages sincere bidding early in the auction, since bids placed early in the auction may emerge as winning bids. When submitting its bids in a round, the bidder is saying that it is happy to win any of the submitted bids, including renewed bids, at the prices bid.

Bid withdrawals are not permitted. In an auction without package bidding, withdrawals were needed as a device for backing out of a failed aggregation. With package bidding, withdrawals are not needed. There is no exposure problem, since the bidder can bid all-or-nothing on a package of complementary licenses.

Allowing package bids is a major change from the original FCC design. Bidder incentives are fundamentally altered. Large bidders, in addition to not facing an exposure problem, have less of an incentive for demand reduction. Small bidders now face a negotiation with each other on how to top large package bids. All bidders will need to rethink their strategies. Relative to the standard auction, which favored small bidders, the package auction favors large bidders.

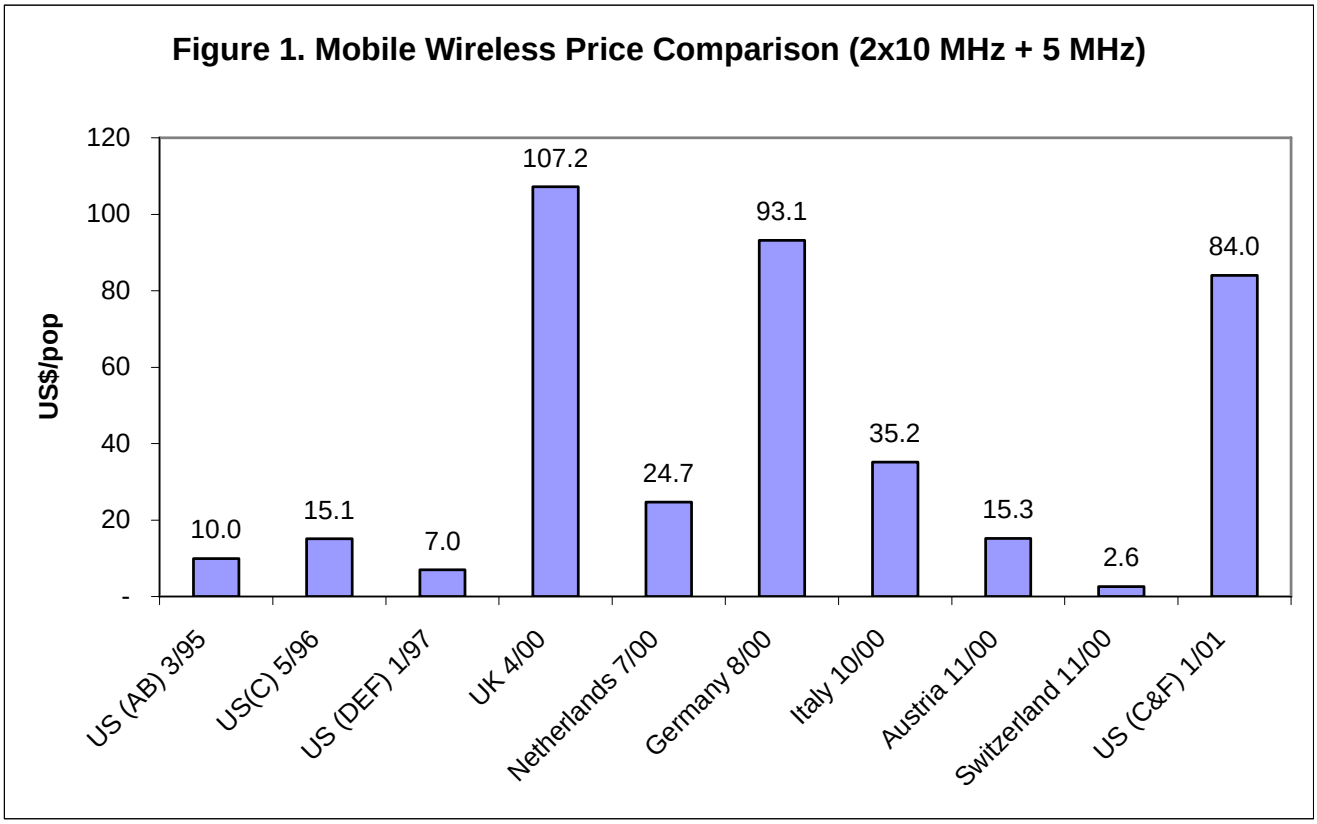
The FCC's package auction is an important innovation. Implementing such an auction poses many challenges for the FCC. It is not surprising that it took several years to introduce package bidding. Even now it is uncertain how well this design will perform in practice compared with the standard auction without package bidding. Whether the package auction is an improvement surely depends on the setting.

8 UMTS auctions in Europe and Asia

European and Asian countries currently are in the process of assigning Universal Mobile Telecommunications System (UMTS) licenses, which will be used for third-generation mobile wireless services. Many countries decided to use an auction to assign the licenses (e.g., UK, Netherlands, Germany, and Switzerland); other countries (e.g., France, Spain, and Sweden) decided on a beauty contest; and still others (e.g., Italy) decided on a hybrid beauty contest/auction. The allocation of UMTS

spectrum is European-wide, although individual countries can determine there own band plans. Nearly all countries are assigning between four and six national licenses.

The early European auctions conducted in 2000 raised nearly $100 billion. An additional expense of at least $100 billion will be required to build the infrastructure necessary to provide service. In countries like the UK and Germany, which fetched the highest prices the license cost per person amounts to about $100 per person. These staggering sums have led many to question the desirability of auctions for assigning spectrum licenses.



In fact, auction prices have varied considerably over time and over markets. This is seen in Figure 1, which presents the per person price of a 20 MHz license (2×10 MHz paired) in several major spectrum auctions.[4] For comparison purposes, Figure 1 also shows past and current US auctions of 2G spectrum. The first three US auctions occurred over three years before the 3G auctions in Europe. The fourth US auction concluded in January 2001 with a price comparable to the highest 3G prices. Part of price

[4] Most of the European licenses also included 5 MHz unpaired spectrum. However, these auctions have shown that the bidders place little value on this unpaired spectrum, so I ignore the unpaired spectrum in the price comparison. In the US C-block auction, bidders received attractive installment payment plans. I discount these prices by 40% to reflect the value of the installment payments.

variation is explained by the different times at which the auctions occurred. Part of the difference in the European prices is explained by the size of the various countries. Markets like the UK and Germany are thought to have more value, even on a per person basis, than the Netherlands and Switzerland. Still there is much variation to explain. The primary determinant of prices appears to be the level of competition going into the auction, rather than the subtle differences in auction design across the various countries. Competition in the auction is largely endogenous, since it is the result of partnership negotiations among potential bidders.

The first countries to auction (UK, Netherlands, and Germany) used a simultaneous ascending auction. In the UK and the Netherlands, the auction design is especially simple, since a bidder can win at most a single license. Hence, there is no incentive for demand reduction.

An incumbent provider of first- and second-generation mobile services in a market tends to have a much higher value for a license than a new entrant. The incumbent's existing infrastructure and customer base yields cost savings in building out a service and attracting customers. Also, an incumbent's failure to win a license would adversely impact its existing business. Hence, it is likely that incumbents will win licenses. As a result, the outcome of the auction depends greatly on the number of licenses that are auctioned relative to the number of incumbents. The UK government initially intended to auction four licenses, but there was a concern that this would damage auction revenues, since potential new entrants might fear that it is pointless to compete against the four strong incumbents. The final design involved the auction of five licenses, which guaranteed that a new entrant would win a license. In contrast, in the Netherlands, there are five incumbents and five UMTS licenses.

The UK UMTS auction was the largest auction in history, generating $35 billion in revenues. Four incumbents and nine potential entrants competed in the auction, which lasted 150 rounds. The four incumbents, British Telecom, Vodafone, Orange, and One 2 One, each won a license, as did the new entrant TIW. Vodafone's 2×15 MHz license sold for $9.5 billion, or $160 per person; the other incumbent licenses sold for similar prices on a per MHz basis. This amount far exceeded industry expectations before the auction. In contrast, the average price paid in 1995 in the FCC's AB auction for a 2×15 MHz license was $15.5 per person, less than one-tenth of the UK price.

Why were the UK prices so high? There are several factors. First, the 1995 price of $15.5 per person in the US is out of date. US prices now are much higher. For example, early in 2000, Nextel offered to buy Nextwave's spectrum for $8.3 billion, a price of about $80 per person. Second, unlike in the US auction, there was no possibility for demand reduction. Bidders had every incentive to bid up to their values. Third and likely most important, the bidding was especially competitive, since this was the first in

a sequence of UMTS auctions throughout Europe. A winner in the UK auction is well positioned for subsequent UMTS auctions. Hence, a bidder can view the UK auction as a foot-in-the-door to Europe. To the extent that a UK license is complementary with UMTS licenses in other countries, then we should expect the UK licenses to sell for a premium, recognizing this complementary value.

In the German auction, each bidder bid for either two or three of the twelve available 2×5 MHz blocks; hence, there will be between four and six winners. The German auction had the apparent advantage that it lets the bidding determine how many UMTS competitors there will be. If competition among new entrants is intense, there can be six winners, presumably the four incumbents plus two new entrants. Jehiel and Moldovanu (2000) argue that the design is biased against new entry, since the incumbents have substantially higher values because of their incumbent position and benefit from excluding new entrants. However, it is possible that the two weakest incumbents may be willing to bid for just two blocks, making room for a new entrant. The question is whether the benefit from demand reduction more than compensates for the reduced profits in a five-player vs. a four-player market. Probably a better design would set-aside two blocks for a new entrant and then let the bidding determine whether there would be four or five winners for the remaining ten blocks.

Following the $35 billion UMTS auction in the UK, the Dutch government expected to raise $8.7 billion in its auction. The Dutch government arrived at this figure by simply scaling down the UK amount for the smaller population in the Netherlands (15 vs. 59 million people). Confident of a huge windfall, the government cancelled its July bond issue. Their confidence may be a mistake. The reality is that the UK and Dutch auctions are quite different despite the fact that both use the simultaneous ascending auction to auction off five third-generation mobile licenses.

In the UK, the guaranteed success of at least one new entrant encouraged participation in the auction. In the Netherlands, with five incumbents bidding for five licenses, the logical outcome is for the five incumbents to win licenses. Recognizing the difficulty of winning a license, potential entrants have strong incentives to partner with the incumbent bidders. This is exactly what happened. Although initially there were several strong potential entrants, all partnered with one of the incumbents before the auction began. The strongest entrant, Deutsche Telecom, partnered with the weakest incumbent, Ben; DoCoMo and Hutchinson partnered with KPN; and NTL was already effectively partnered with Dutchtone (France Telecom has a large interest in both). This left one weak entrant in the bidding. At the beginning of the auction, just six bidders were competing for five licenses: five strong incumbents and one weak potential entrant (Versatel).

To make matters worse, the government specified minimum opening bids that decline in the first three rounds if a license does not receive a bid. The two large licenses (15 MHz-paired) start at 100 million guilders, but fall to 75 after one round of inactivity, 35 after two rounds, and 0 after three rounds; similarly, the three 10 MHz-paired licenses start at 90, but drop to 60, 30, and then 0, with each round of inactivity. Bidders were given three waivers of the activity rule that otherwise would require them to be active in each round.

The strategic use of waivers in this environment should be obvious. Even if the other five bidders bid in the first round, it is extremely unlikely that each of the five licenses would receive a bid. Hence, by using a waiver in the first round, a bidder can get the minimum opening bid to drop substantially. In fact, five of the six bidders saw this strategy. Only Libertel bid in the opening round, placing a 100 million guilder bid on B. (Libertel is 70% owned by Vodafone, the company that won the B license in the UK auction.) In the second and third rounds, the five bidders that needed to bid again used waivers. So going into the fourth round, the minimum bids were 0 on all licenses, but the B license, which stood at 110 million guilders. After 175 rounds of bidding, the three 10 MHz licenses were priced at $1/8^{th}$ of the minimum opening bid (11 million guilder).

The Dutch auction rules also did not include the customary language that the auctioneer has the right to cancel the auction at any time. If Versatel decides to drop out at low prices the auction will end at only a tiny fraction of the $8.7 billion figure the government is hoping for.

The 3G auctions provide an excellent test of auction theory with multiple items. These auctions have been strategically simple and are extremely high stake. For example, the German and Austrian 3G auctions—as well as an earlier 2G German auction—provided relatively clean tests of demand reduction. The theoretical predictions on demand reduction were borne out empirically in the final outcomes of these auctions. At the same time, one would have imagined that all of the bidding behavior, at least by the eventual winners, could be easily understood as equilibrium behavior in a profit-maximizing model. However, this does not always appear to be the case.

One explanation for non-profit maximizing bidding is the principal-agent problem between the shareholders and the CEO making the bidding decisions (Ausubel and Cramton 2001). At times the CEO may not fully represent shareholder interests. For example, CEO's may sometimes fail to fully appreciate the economics of demand reduction, and fail to reduce demand as early as they should. In particular, in the German auction, Deutsche Telekom (DT) was in a position to likely end the German auction by dropping from demanding three blocks to demanding two blocks, at well before the final prices. Instead, DT continued bidding for three blocks for a time, ultimately buying the two blocks that it could have

bought earlier, but paying about $2 billion more. This bidding behavior may have more to do with the preferences (and fears) of the CEO, rather than the interests of the shareholder.

A second source of distortion is that the CEO simply acts as humans do in auctions, making some of the same mistakes that are frequently observed in the laboratory (Kagel and Roth 1995). An example similar to the DT example, but with a different outcome occurred in the US C&F auction. In New York, three licenses were up for bid. After round 14, only the three largest bidders (Verizon, Cingular, and AT&T) were competing for the three licenses. At this point prices were at $782 million. Verizon, however, continued to bid for two licenses throughout the auction, creating excess demand until Cingular finally dropped out when Verizon's price exceeded $2 billion per license. Why did Verizon continue to push the price up on both of its licenses rather than ending the bidding at a fraction of the eventual price? One explanation is that the Verizon CEO felt that he would look bad, pushing the prices up and then eventually settling for one license. This gives the CEO an incentive to "throw good money after bad," a phenomenon for which there is ample experimental support.

9 Advice to governments

Important lessons about spectrum auction design can be gleaned from recent experience.

9.1 Allocating the spectrum is just as important as its assignment

There are two steps in making spectrum available to companies. The first step is the allocation of the spectrum for licensing. The allocation defines the license (the frequency band, the geographic area, the time period, and the restrictions on use). The second step is assigning the licenses to particular companies. Although my focus has been on assigning the licenses, since that is what the spectrum auctions are asked to do, the allocation step often is more important. Arguably the greatest economic gains will come from better allocation of spectrum, rather than from improved methods of assigning the spectrum. This is because current spectrum auctions already are highly efficient. In contrast spectrum allocations often are far from efficient.

Determining spectrum allocations involves complex political, engineering, and economic factors. Finding suitable spectrum for new uses is difficult. Often there are incumbent spectrum users. Ideally, one would want market-based tests to determine what spectrum should be auctioned and how it should be structured, but such tests are hard to construct. Political compromises frequently trump good economics. This is especially the case when the competing uses include several constituencies, such as broadcasting, commercial, public safety, and military use.

Finally, the allocation can have a pronounced effect on the success of a particular auction design. For example, having five licenses in the UK UMTS auction, rather than four, was critical in stimulating competition (Klemperer 1998).

9.2 Use care when modifying successful rules

Simultaneous ascending auctions overall have been highly successful in the US and many other countries. Recent FCC auction rules should be a starting point for any government considering spectrum auctions. Modifications to the rules should be considered carefully. The various rules interact in often subtle ways. An apparently innocent change can have disastrous consequences. The interaction between waivers and the declining schedule of minimum opening bids in the Dutch UMTS auction is an example.

Still it is important to recognize that different settings often require a different auction design, as is emphasized in Klemperer (2000). For example, an ascending auction may be inappropriate in situations where competition is weak (Cramton 1998).

9.3 Allow discretion in setting auction parameters

The simultaneous ascending auction has a number of parameters (minimum opening bids, minimum bid increments, activity requirements, and rounds per day) that let the government control the pace of the auction. It is fine for the government to specify guidelines on how it is likely to set parameters, but eliminating all discretion is a bad idea. There are simply too many unknowns going into the auction for the government to specify all parameters in advance. The parameters should be adjusted during the auction to balance the goals of a timely assignment and an efficient assignment. The bidders need time to adjust strategies in light of information revealed in the bidding. Too much haste may lead to bidder error and inefficient assignments. Time also may be needed for bidders to secure additional capital if prices are higher than expected. On the other hand, setting the bid increment too low (e.g., 1%) near the end of the auction can result in days of bidding without much progress.

9.4 Reduce the effectiveness of bidders' revenue-reducing strategies

The information and flexibility available to the bidders in a simultaneous ascending auction is a two-edged sword. Although desirable in reducing bidder uncertainty and promoting efficient license aggregations, the information and flexibility—in certain circumstances—can be used to reduce auction prices. In particular, revenue-reducing strategies may be effective when bidder competition is weak and when bidders already have a sense of who should win what. In this case, the auction is best thought of as

a negotiation among the bidders, in which bidders are only able to communicate through their bids. The auction ends when there are no disagreements about who should win what.

As discussed earlier, one common revenue-reducing strategy is demand reduction: the tendency for a bidder to reduce its spectrum demands, knowing that demanding less will tend to reduce spectrum prices. This is a unilateral strategy that is best addressed in the choice of the band plan and geographic scope of the licenses. License structures that make it more difficult for the bidders to split up the spectrum are less vulnerable to demand reduction. For example, offering large nationwide licenses, in which no bidder can win more than one, prevents the bidders from splitting up the spectrum at auction.

The second revenue-reducing strategy is retaliation. This can be thought of as coordinated demand reduction. It is sending another bidder the message that they should stay off your licenses, if they want you to stay off their licenses. Retaliation is especially clear in early auctions where it is possible to use the trailing digits of bids to identify relevant markets. The bidders are effectively able to say things like, "I'll stay out of New York, if you stay out of Los Angeles." This tactic is eliminated by truncating bids to three significant digits, or only allowing bids in integer multiples of the bid increment. However, it is still possible for bidders in certain circumstances to use retaliation to keep prices low. Retaliation is best minimized through careful choice of activity rules, minimum opening bids, and bid increments. An anonymous auction can be used in settings where collusion is likely.

9.5 Use spectrum caps to limit anticompetitive concentration

A spectrum cap is a direct method of limiting the concentration of spectrum for a particular type of service in a particular area. Its advantage is that it is a bright-line test that is easy to enforce, both before and after the auction. In the US, it has played a critical role in ensuring that there are many competitors for mobile wireless services in each market. This competition has led to clear gains for consumers. Its disadvantage is that it is overly simplistic. Spectrum caps cannot take into account the specifics of each situation, and determine whether consumers would be made better or worse off with greater concentration of ownership.

The best policy on spectrum caps is a middle ground, where binding caps are imposed in initial auctions, but then these caps give way once it is believed that vigorous competition has been established. Then individual mergers can be reviewed on a case-by-case basis.

In setting and revising spectrum caps, governments should err on the side of too stringent a cap, since it is much harder to break up a firm than to allow a merger. If concentration is viewed as a potential problem going into an auction, then spectrum caps, rather than case-by-case review, must be used, since

only caps can provide an instantaneous determination of what is allowed and what is not. Such a rapid response is essential in a simultaneous ascending auction. Bids must be binding commitments until they are topped. Hence, at every point in the auction, the bidders must know what is allowed and what is not.

Typically, spectrum caps lower auction revenues, but there is one important exception. In situations where incumbent bidders have an advantage, a spectrum cap may actually increase revenues and promote efficiency. In such a situation without a spectrum cap, non-incumbents may be unwilling to participate in the auction, knowing that the incumbents will ultimately win. As a result, in the auction without the cap only the incumbents show up, there is a lack of competition, and the incumbents split the licenses up among themselves at low prices. With the cap, the non-incumbents know that non-incumbents will win licenses, giving them the incentive and ability to secure the needed financing from capital markets. A competitive auction with market prices results. This phenomenon of incumbent bidders getting good deals, because of a lack of non-incumbent competition has been seen in some US auctions, but is most vivid in the Dutch UMTS auction.

9.6 Implement special treatment for designated entities with care

One of the auction objectives that the US Congress gave the FCC is to have a diversity of auction winners. The FCC was instructed to encourage participation by small businesses and women- or minority-owned firms, so called “designated entities.”

While small and diverse owners may well be a desirable goal for broadcast media with editorial content, the same arguments likely do not apply to mobile wireless communications. Special treatment to designated entities is to some extent premised on the idea that small is beautiful. But what we have learned in the last several years is that there are significant scale economies in wireless communications. Part of the scale economy is the bargaining advantage it creates with equipment suppliers. Another part is scale economies in marketing. But perhaps the largest is the value that consumers place on seamless roaming. As a result, the marketplace has shifted toward nationwide services in most wireless categories. These nationwide services are necessarily billion dollar deals, or tens-of-billions in the case of broadband mobile services. What consumers need is a variety of strong national competitors. In many cases, the small regional players cannot compete. The designated entity rules may simply be setting up the small businesses for failure. This is not desirable, especially given that the FCC’s unjust enrichment rules, discussed below, effectively prevent resale to the higher-valued use should failure occur.

On balance, the best policy may be to abandon favors to designated entities, and to use spectrum caps to guarantee new entry where desirable and to prevent over-consolidation of spectrum. An alternative is to offer non-incumbents bidding credits to encourage new entry. My reason for this

conclusion has to do with the practical difficulties of effectively implementing favors for designated entities, which I discuss below.

The FCC has used bidding credits, set-asides, and installment payments to encourage the participation and success of designated entities. The idea is that without special treatment, these small businesses would find it difficult to compete with the large incumbents. The favored treatment can serve to "level the playing field," and thereby foster innovation and intensify competition.

Although this is a valid point in theory, and even has some empirical support (Ayres and Cramton 1996), governments must be cautious when using favors for designated entities. A vivid example is the FCC's only major setback, the C-block broadband PCS auction. (Other disappointing auctions were IVDS and WCS, but none have involved the economic loss seen in the C-block.) The auction failed largely because of overly attractive installment payments (10% down and 6-year interest-only at the risk-free 10-year Treasury rate). This encouraged speculative bidding, which led to all the major bidders defaulting and declaring bankruptcy. Even now, years after the auction, much of this C-block spectrum lies unused, tied up in bankruptcy litigation. Installment payments were a bad idea, because they advantaged the bidders with the most speculative business plans. In addition, installment payments put the FCC in the role of banker, an activity for which the FCC has no advantage. Since the C-block experience, the FCC no longer offers installment payments.

The two other instruments to favor designated entities—set-asides and bidding credits—may be desirable in special situations. The typical situation is one where the government is attempting to encourage competition in the auction and the post-auction market for wireless services. By leveling the playing field between incumbents and new entrants, competition may be enhanced.

Still, set-asides and bidding credits have serious potential problems. Gauging the right level of set-asides or bidding credits is extremely difficult. Also, it is nearly impossible to target the favor to the desired group. The creation of fronts, carefully constructed to satisfy the rules but circumvent their intent, has been a constant problem in the FCC auctions.

One general rule, whether using set-asides or bidding credits, is that it is best for incumbents and non-incumbents to compete in the same auction. Then if competition among non-incumbents is sufficiently robust, the non-incumbents will be able to spill over to the licenses that incumbent bidders can bid on. This spillover increases competition, and hence revenues in the auction.

Another problem with favors for designated entities is their impact on the resale of spectrum. The FCC auction rules prohibit resale to a non-designated entity for a period of time, and include an "unjust

enrichment" provision that requires that the FCC be paid back the bidding credit plus interest. The reality has been that the bidding credits are often bid away by competition among designated entities. Indeed, even after accounting for the value of the installment payments and the bidding credits, the C auction resulted in prices that were well above what the large firms paid in the AB auction. Given these facts, it is difficult to understand why the small firms are required to pay a huge "unjust enrichment" penalty, when there is no unjust enrichment. As it stands, the penalty is so large that it is often an insurmountable barrier to trade.

Perhaps the most serious problem with favors to designated entities is that they greatly complicate the auction process. Too often the rules for designated entities become a central issue in establishing the auction procedures. These rules are complex. They are difficult to write, difficult to enforce, and difficult to defend. The absolute worst outcome in a spectrum auction is having the licenses tied up in litigation. Until the litigation is resolved the building of communication services cannot begin. Even the risk of litigation can have a disastrous effect on auction participation, and hence revenues.

9.7 Implementing an effective auction takes time and involves difficult tradeoffs

A second FCC auction disappointment was the Wireless Communication Services (WCS) auction, held in April 1997. Revenues in this auction were a tiny fraction of what they might have been. The main problem was the stringent out-of-band emission limit. Equipment manufacturers warned that this would threaten the commercial viability of this spectrum. The low prices at auction and the absence today of activity in this band appears to confirm that the equipment manufacturers were right. At the time of the decision, the FCC was facing a difficult tradeoff between the rights of prior winners of neighboring licenses and the WCS use. Such decisions are always difficult, but the FCC was under intense time pressure to meet the timetable that Congress set for the auction. This aggressive timetable may well have led the FCC to make a too-hasty decision on interference rules, which damaged the value of this spectrum. Congress's desire for receiving revenues according to its fiscal calendar may have resulted in substantially reduced auction revenues.

9.8 Facilitate efficient clearing when auctioning encumbered spectrum

An issue of increasing importance is the auctioning of encumbered spectrum. Many of the FCC auctions are for overlay licenses (the PCS and 700 MHz auctions are examples). An overlay license is for the portions of the band that are not occupied by incumbent licensees. Effectively the FCC is auctioning Swiss cheese, where the holes are incumbent licensees with particular rights. These incumbents must either be cleared or worked-around in order for the new entrant to provide a service. Negotiations

between the new entrant and the incumbent are often difficult due to holdout by the incumbent. A second problem occurs when multiple new entrants benefit from the clearing of a single incumbent; then each new entrant can hope to free-ride on the clearing done by others. These problems often prevent or delay the efficient clearing of the spectrum.

The government can play an important role in adopting rules that promote the efficient clearing of the spectrum by structuring the rules of negotiation appropriately (Cramton et al. 1998). The broadband PCS rule-making is a good example. The FCC adopted rules that went a long way in minimizing the holdout and free-rider problems that undermine efficient clearing. New licensees were given the right to move an incumbent after a period of time, compensating the incumbent for its relocation costs. This rule minimizes the need for costly negotiations.

The upcoming 700 MHz auction is a more difficult case. This spectrum currently is used for analog television channels 60-69. The spectrum cannot be used for new services until the analog broadcasters terminate over-the-air broadcasting on these channels. Because of the political power of broadcasters, the FCC was unwilling to adopt PCS-type rules that promote efficient clearing. As a result, clearing will be much more costly and inefficient.

9.9 Promote market-based tests in spectrum management

Spectrum auctions are a critical step in the march toward market-based spectrum management. Governments should continue on this path. Flexibility should be the norm, not constraints. Constraints should appear only when those constraints help foster a more competitive environment by adding essential structure. (A good example of the benefits of structure is the success of GSM in Europe.) Specifically, governments should:

- Allow service flexibility
- Allow technical flexibility
- Set initial interference rules, but allow trading
- Set initial geographic and bandwidth scope to an ex ante view of how spectrum will be used, but allow spectrum partitioning and geographic disaggregation
- Eliminate buildout requirements
- Allow transfers of licenses

Many of the current restrictions are holdovers from the days of comparative hearings. These needless regulations should be eliminated. The rate of technological change is now so great that attempting to craft specific regulations as was done in the past is hopeless and destructive. Rather, governments should focus on broad principles that encourage competition. Legislatures especially should refrain from the micro-management of spectrum policy. The complex economic and engineering tradeoffs are much better left to a specialized agency.

10 Conclusion

Spectrum auctions represent a huge advance in the way governments allocate scare resources. Despite some early bumps, spectrum auctions largely have succeeded in putting spectrum in the hands of those best able to use it. Economists have made (and continue to make) valuable contributions to spectrum auction design. The simultaneous ascending auction, pioneered by the FCC, has been remarkably successfully in the US and other countries. Its simple process of price discovery promotes efficiency, especially in competitive auctions in which bidders do not have large and varied license synergies. The recent introduction of package bidding to this successful format promises to extend the set of environments where the simultaneous ascending auction performs well.

In most cases, the greatest room for improvement lies not in the auction design, but in the allocation process. Spectrum allocations often are the result of political forces that ignore the underlying economics. Governments would do well to let competitive market forces, not political lobbying, determine spectrum use. The auctioning of spectrum is a major step in the right direction.

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