Simultaneous Ascending Auctions

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Abstract

The simultaneous ascending auction has proved to be a successful method of auctioning many related items. Simultaneous sale and ascending bids promote price discovery, which helps bidders build desirable packages of items. Although package bids are not allowed, the auction format does handle mild complementarities well. I examine the auction design and its performance in practice.

1 Introduction

This chapter examines one of the most successful methods for auctioning many related items—the simultaneous ascending auction. This auction form was first developed for the U.S. Federal Communications Commission's spectrum auctions, beginning in July 1994, and has subsequently been adopted with slight variation for dozens of spectrum auctions worldwide, resulting in revenues in excess of $200 billion. The method, first proposed by Paul Milgrom, Robert Wilson, and Preston McAfee, has been refined with experience, and extended to the sale of divisible goods in electricity, gas, and environmental markets. Here I describe the method and its extensions, provide evidence of its success, and suggest what we can learn from the years of experience conducting simultaneous ascending auctions.

It might seem odd for the simultaneous ascending auction to appear as a method for combinatorial auctions, since a key feature of the simultaneous ascending auction, at least in its basic form, is the requirement that bids be for individual items, rather than packages of items. As a result, the simultaneous ascending auction exposes bidders to the possibility that they will win some, but not all, of what they desire. In contrast, all the other combinatorial auction methods discussed in this book, eliminate this exposure problem by allowing bidders to bid on packages of items. Nonetheless, I view the simultaneous ascending auction, not as a historical curiosity to be supplanted by more powerful combinatorial methods, but as an essential method any auction designer should have in his toolkit. The simultaneous ascending auction (and its variants) will remain the best method for auctioning many related items in a wide range of circumstances, even settings where some of the goods are complements for some bidders, so the exposure problem is a real concern.

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This is not to say that true combinatorial auctions—those that allow package bids—are not also important. They are. Rather, my point is that there are many situations where the simultaneous ascending auction will do a sufficiently good job in limiting the exposure problem that its other advantages (especially simplicity and price discovery) make it a preferred auction method. In other settings, where complementarities are both strong and varied across bidders, package bids are needed to improve the efficiency of the auction mechanism.

The simultaneous ascending auction is a natural generalization of the English auction when selling many goods. The key features are that all the goods are on the block at the same time, each with a price associated with it, and the bidders can bid on any of the items. The bidding continues until no bidder is willing to raise the bid on any of the items. Then the auction ends with each bidder winning the items on which it has the high bid, and paying its bid for any items won.

The reason for the success of this simple procedure is the excellent price discovery it affords. As the auction progresses bidders see the tentative price information and condition subsequent bids on this new information. Over the course of the auction, bidders are able to develop a sense of what the final prices are likely to be, and can adjust their purchases in response to this price information. To the extent price information is sufficiently good and the bidders retain sufficient flexibility to shift toward their best package, the exposure problem is mitigated—bidders are able to piece together a desirable package of items, despite the constraint of bidding on individual items rather than packages.

Perhaps even more importantly, the price information helps the bidders focus their valuation efforts in the relevant range of the price space. This benefit of price discovery is ignored in the standard auction models, which assume that each bidder costlessly knows his valuation for every possible package (or at least knows how his valuation depends on the information of others in the case of non-private value models). However, in practice, determining values is a costly process. When there are many items, determining precise values for all possible packages is not feasible. Price discovery focuses the bidders' valuation efforts to the relevant parts of the price space, improving efficiency and reducing transaction costs.

To further mitigate the exposure problem, most simultaneous ascending auctions allow bidders to withdraw bids. This enables bidders to back out of failed aggregations, shifting bids to more fruitful packages. However, I find that bid withdrawals often facilitate undesirable gaming behavior, and thus the ability to withdraw bids needs to be constrained carefully. It is my view that price discovery—not bid withdrawal—is the more effective way to limit the exposure problem in simultaneous ascending auctions.

Since July 1994, the Federal Communications Commission (FCC) has conducted dozens of spectrum auctions with the simultaneous ascending format, raising tens of billions for the U.S. Treasury. The auctions assigned thousands of licenses to hundreds of firms. These firms provide a diversity of wireless communication services now enjoyed by a majority of the population. 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 and most have been simultaneous ascending auctions. (See Cramton 1997 and Milgrom 2004 for a history of the auctions.)

There is now substantial evidence that this auction design has been successful. Resale of licenses has been uncommon, suggesting the auction assignment is nearly efficient. 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 items.

Despite the general success, the simultaneous ascending 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 items. I identify problems with the simultaneous ascending auctions, and discuss how to minimize these problems.

I begin by motivating the design choices in a simultaneous ascending auction and discuss an important extension, the simultaneous clock auction, for the sale of many divisible goods. Then I describe typical rules, including many important details. Next I examine the performance of the simultaneous ascending auction, identifying both strengths and weaknesses of the approach. I discuss many refinements to the auction method, which have been introduced from early experience.

2 Auction design

The critical elements of the simultaneous ascending auction are (1) open bidding, (2) simultaneous sale, and (3) no package bids. These features create a Walrasian pricing process that yields a competitive equilibrium provided (1) items are substitutes, (2) bidders are price takers, and (3) bid increments are negligible (Milgrom 2000, 2004). Of course, these conditions do not hold in practice. Some degree of market power is common, at least some items are complements, and bid increments in the 5 to 10 percent range are required to get the auction to conclude in a manageable number of rounds.

Still the simultaneous ascending auction does perform well in practice largely because of the benefits of price discovery that come from open bidding and simultaneous sale. These benefits take two forms.

First, in situations where bidder values are interdependent, price discovery may reduce the winner's curse and raise revenue (Milgrom and Weber 1982). Bidders are able to bid more aggressively, since they have better information about the item's value. More importantly, when many items are for sale, the price discovery lets bidders adapt their bidding and analysis to the price information, which focuses valuation efforts and facilitates the aggregation of a complementary package of items.

The alternative of sequential sale limits information available to bidders and limits 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 item values are interdependent. A sequential auction also eliminates many strategies. A bidder cannot switch back to an earlier item 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.

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.

Almost all the simultaneous ascending auctions conducted to date do not allow package bids. Bids are only for individual items. The main advantages of this approach is simplicity and anonymous linear prices. The auction is easily implemented and understood. The disadvantage is the exposure problem. 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. Bidding on individual items 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. He 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, he will “win” one spot, losing an amount equal to his 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 with a bid of $75 for the package.

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

Unfortunately, allowing package bids creates other problems. Package bids may favor bidders seeking large aggregations due to a variant of the threshold problem. 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 spots, 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.

Package bidding also adds complexity. Unless the complementarities are large and heterogeneous across bidders a simultaneous ascending auction without package bids may be preferred.

2.1 Clock auctions

An important variation of the simultaneous ascending auction is the simultaneous clock auction, discussed in greater detail in Chapter 5. The critical difference is that bidders simply respond with quantities desired at prices specified by the auctioneer. Clock auctions are especially effective in auctioning many divisible goods. There is a clock for each divisible good indicating its tentative price per unit quantity. Bidders express the quantity desired at the current prices. For those goods with excess demand the price is raised and bidders again express their desired quantities at the new prices. This process continues until supply just equals demand. The tentative prices and assignments then become final.

If we assume no market power and bidding is continuous, then the clock auction is efficient with prices equal to the competitive equilibrium (Ausubel and Cramton 2004).

Discrete, rather than continuous rounds, means that issues of bid increments, ties, and rationing are important. This complication is best handled by allowing bidders in each round to express their demand curves for all points along the line segment between the start of round prices and the end of round prices. Allowing a rich expression of preferences within a round makes bid increments, ties, and rationing less important. Since preferences for intermediate prices can be expressed, the efficiency loss associated with the discrete increment is less, so the auctioneer can choose a larger bid increment, resulting in a faster and less costly auction process.

A second practical consideration is market power. Although some auction settings approximate the ideal of perfect competition, most do not. The auction design needs to address market power issues. Two useful instruments are information policy and reserve pricing. By controlling the information that the bidders receive after each round of the auction, the auctioneer can enhance the desirable properties of price and assignment discovery, while limiting the scope for collusive bidding. Reserve pricing serves two roles, providing price discipline in the absence of competition and discouraging collusion by limiting the maximum gain from successful collusion.

3 Typical rules

The simultaneous ascending auction works as follows. A group of items with strong value interdependencies are up for auction at one time. A bidder can bid on any collection of items 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 item. This auction form was thought to give the bidders flexibility in expressing values and building packages of items. Common rules are described below.

Quantity cap. To promote competition in the aftermarket, a bidder often is limited in the quantity it can win.

Payment rules. Typically payments are received at least at two times: a refundable deposit before the bidding begins and a final payment for items won. The refundable deposit often defines the bidder's initial eligibility—the maximum quantity of items that the bidder can bid for. A bidder interested in winning a large quantity of items would have to submit a large deposit. The deposit provides some assurance that the bids are serious. Some auctions require bidders to increase the deposit as bids increase.

Minimum bid increments. To assure that the auction concludes in a reasonable amount of time, minimum bid increments are specified. Bid increments are adjusted in response to bidder behavior. Typically, the bid increments are between 5 and 20 percent.

Activity rule. The activity rule is a device for improving price discovery by requiring a bidder to bid in a consistent way throughout the auction. It forces a bidder to maintain a minimum level of activity to preserve its current eligibility. A bidder desiring a large quantity at the end of the auction (when prices are high) must bid for a large quantity early in the auction (when prices are low). As the auction progresses, the activity requirement increases, reducing a bidder's flexibility. The lower activity requirement early in the auction gives the bidder greater flexibility in shifting among packages early on when there is the most uncertainty about what will be obtainable.

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.

Stopping rule. A simultaneous stopping rule is used to give the bidders maximum flexibility in pursuing backup strategies. The auction ends if a single round passes in which no new bids are submitted on any item. In auctions with multiple stages (later stages have higher activity requirements), the auction ends when no new bids are submitted in the final stage. Few or no bids in an earlier stage shifts the auction to the next stage.

Bid information. The most common implementation is full transparency. Each bidder is fully informed about the identities of the bidders and the size of the deposits. 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.

Bid withdrawal. To limit the exposure problem, the high bidders can withdraw their bids subject to a bid withdrawal penalty. If a bidder withdraws its high bid, the auctioneer is listed as the high bidder and the minimum bid is the second-highest bid for that item. The second-highest bidder is in no way responsible for the bid, since this bidder may have moved on to other items. If there are no further bids on the item, the auctioneer can reduce the minimum bid. 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 seller as a result of the withdrawal.

4 Performance of the simultaneous ascending auction

Since we do not observe the values firms place on items, it is impossible to directly assess the efficiency of the simultaneous ascending auction from field data. Nonetheless, we can indirectly evaluate the auction design from the observed behavior in spectrum auctions (Cramton 1997, McAfee and McMillan 1996). I focus especially on the three US PCS broadband auctions, which I refer to as the AB auction, the C auction, and the DEF auction, indicating the blocks of spectrum that were assigned in each. This spectrum is used to provide mobile wireless voice and data communications.

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 items.

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) 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 simultaneous ascending 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.

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. These issues become important in 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.

For example, suppose there are two identical items and two bidders (Large and Small). Large has a value of $100 per item ($200 for both); whereas small has a value of $90 for one item and values the second at $0. In a simultaneous ascending auction with a reserve price less than $80, the unique equilibrium outcome is for each to bid for a single item, so that the auction ends at the reserve price. Large prefers ending the auction at the reserve price, winning a single item for a profit of more than $20, since to win both items Large would have to raise the price on both items above $90 (it is a dominant strategy for Small to bid up to $90 on each), which results in a profit of less than $20. The demand reduction by Large harms both efficiency and seller revenues.

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 items 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 simultaneous ascending auction can be viewed as an ascending-bid version of a uniform-price auction. Certainly, for items that are close substitutes, the simultaneous ascending auction has generated near uniform prices. 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). To illustrate this, consider a simple example with two identical goods and two risk-neutral bidders. Suppose that for 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 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 the clearing price. Each bidder will win the number of units he demands when the auction ends, and is charged the clearing price for each unit he wins. In this game, if 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 and Grimm et al. 2002).

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 value 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 (1998) and Brusco and Lopomo (2002) 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 items 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 (2002) 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 and efficiency.

The DEF auction was especially vulnerable to collusive bidding, since 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, as well as subsequent 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 (2002) found that bidders who commonly use these strategies paid less for the spectrum they ultimately won. Further evidence that retaliation was effective in reducing prices is seen by the absence of arbitrage between the identical D and E blocks in each market. In particular, 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 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. Such extreme bundling may have negative efficiency consequences, but improve revenues.

The inefficiencies of demand reduction can be eliminated with a Vickrey auction or more practically with an ascending proxy auction or a clock-proxy auction (see Ausubel and Milgrom 2002 and Chapters 1, 3 and 5).

6 Lessons learned and auction enhancements

The FCC auction rules have evolved in response to the experience of several 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 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 initially broke 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 now uses a random tie-breaking rule.

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 three ways: (1) as a signal of the bidder's willingness to give up one license in exchange for another, (2) as part of a parking strategy to maintain eligibility without bidding on desired licenses, and (3) to acquire near the end of the auction more preferred licenses that seem to free up after the decline of another bidder. The 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.

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 Conclusion

A simultaneous ascending auction is a sensible way to auction many items. This approach has been used with great success in many high-stake auctions in the last ten years to auction spectrum, energy, and pollution permits. The process yields a competitive equilibrium in simple settings. Evidence from practice suggests that the desirable properties of the design are largely robust to practical complications, such as mild complementarities. However, when competition is weak, then there is a tendency for collusive bidding strategies to appear, especially in the fully transparent implementation in which all bids and bidder identities are revealed after each round.

When some items are complements, the simultaneous ascending auction suffers from the exposure problem, since package bids are not allowed. To limit this problem, the auction rules typically allow the withdrawal of standing high bids. This allows a bidder to back out of a failed aggregation. Interestingly, an examination of withdrawals in the FCC spectrum auctions reveals that the withdrawals typically were not used for this desired purpose, but rather were mostly for undesirable bid signaling. As a result, current auctions limit a bidder's withdrawals to occur in just a few rounds of the auction.

Recent experience with simultaneous ascending auctions suggests that there are many advantages to the clock variation (Ausubel and Cramton 2004). Most importantly, the ability of bidders to engage in tacit collusion through bid signaling is greatly reduced. Demand reduction, however, remains a problem in the standard clock auction. However, demand reduction can be eliminated by adding a final proxy round at the end of the clock auction. This innovation is the subject of the next chapter.

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