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Auction Design and Tacit Collusion in FCC Spectrum Auctions
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ABSTRACT

The Federal Communications Commission (FCC) has used auctions to award spectrum since 1994. During this time period, the FCC has experimented with a variety of auctions rules including click box bidding and anonymous bidding. These rule changes make the actions of bidders less visible during the auction and also limit the set of bids which can be submitted by a bidder during a particular round. Economic theory suggests that tacit collusion may be more difficult as a result. We examine this proposition using data from 4 auctions: the PCS C Block, Auction 35, the Advanced Wireless Service auction and the 700 Mhz auction. We examine the frequency of jump bids, retaliatory bids and straightforward bids across these auctions. While this simple descriptive exercise has a number of limitations, the data suggests that these rule changes did limit firms' ability to tacitly collude.

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1 Introduction

Starting in 1994, the Federal Communications Commission (FCC) has used auctions to award spectrum. Prior to this time, the FCC used administrative hearings or lotteries to award licenses. Economic theory suggests that auctions should have a number of advantages over these earlier mechanisms. First, in many auction models, game theory predicts that the bidder which values the item most highly will win the auction. Therefore, the auction results in an efficient allocation. Second, auctions generate higher revenues than lotteries or administrative hearings by making firms pay for the right to own licenses. We note that the most recent 700 MHz auction generated \$19.1 billion dollars in revenues. Finally, auctions have clear and transparent rules for awarding licenses. This minimizes the possibility for corruption and economizes on inefficient influence costs from persuading administrative boards.

Over the past decade, a large theoretical literature on spectrum auctions has emerged (See Milgrom (2004) for an excellent survey). An important, but often ignored, aspect of auction design is preventing collusion among bidders (see Marshall and Marx (2007)). Auctions have highly transparent information about both prices and quantities which facilitates the ability of colluders to monitor each others' actions and punish deviations from collusive agreements. For example, in the PCS C-Block auction (Auction 5), bidders submitted roughly 30,000 bids in 183 rounds. The bid amounts and the identity of the bidders were publically observable during the course of the auction. Avery (1998) demonstrated that jump bids may soften competition in ascending auctions serving as a tool to signal bidder valuations. Brusco and Lopomo (2002) characterize collusive equilibria which can be sustained with bidders' ability to observe their opponents' deviation from collusive behavior.¹

Since the first spectrum auctions in 1994, the FCC has modified the auction rules in ways might make it more difficult for bidders to tacitly collude.² First, in auction 16 the FCC introduced click box bidding. Under these rules, the bidders are allowed to increase their bids by fixed increments. Bidders were given 9 possible bid increments from which to choose. Click box bidding limits the opportunities for jump bidding. In a given round, they were allowed to increase their bid by at most 90 percent. Also, click box bidding makes "code bidding" more difficult. In auction 11 (the DEF block), bidders were allowed to freely choose their

¹Ausubel and Cramton (1998) consider demand reduction as a strategy that softens competition. We do not differentiate demand reduction from collusive behavior explicitly although implementation of the strategy of demand reduction does not involve coordination among bidders in contrast to tacit collusion.

²The FCC adopted explicit anti-collusion rules that prohibits bidders that applied for common markets from collaborating, discussing or disclosing their bidding strategy. The rules also require participants to identify any parties with whom they entered into consortium arrangements, joint ventures and any explicit or implicit agreements. While this anti-collusion rule concerns bidding cartel, we focus on changes in auctions rules that concerns tacit collusion.

bid. In many cases, their bids included 7 or more figures and the tailing digits were used to communicate their intentions to rivals. For example, if a bidder intended to vigorously defend license 451, it might include 451 as the last 3 digits of at the end of its bids. This is obviously mechanically impossible using click box bidding.

A second rule change is anonymous bidding which was introduced in the 700 MHz auction. In anonymous bidding, the identities of the bidders is no longer publically observed. This limits the ability of a firm to retaliate against rivals for bidding on its preferred licenses. Game theoretic models of collusion, such as Greene and Porter (1984) frequently require the threat of retaliation from the collusive agreement in order to sustain collusion in equilibrium. If it is more difficult to monitor the actions of other bidders, it will be more difficult to sustain collusive equilibrium via retaliation.

A third rule change regards the size of minimum opening bids. The presence of relatively large minimum opening bids increases the possibility of overpaying or a risk of a financial loss when bidders bid on licenses that they do not desire to explore chances to reduce their payment by gaming the auction format. One example of such behavior is called “parking” which refers to the bidding behavior of delaying bidding for licenses they desire until late rounds to soften competition over those licenses.

In this paper, we examine bids from 4 different spectrum auctions. Our research goal is to examine the relationship between changes in the rules and the frequency of anti-competitive bidding strategies. The auctions include the PCS C Block, Auction 35, the Advanced Wireless Service auction and the 700 MHz auction. These auctions are the largest in terms of revenue generated and took place between 1994 and 2008. As a result, we see a variety of different rules used by the FCC, which differ in their susceptibility to collusion. We will examine the frequency of jump bids, the proportion of bids that are “straightforward” and we will search for evidence of retaliatory bids.

If we observe fewer “collusive” strategies, this suggests that the rule changes may have made it more difficult for firms to collude. Of course, given the available data, our methods do not allow us to directly test for the frequency of collusion. The items sold and the cellular industry also varied in addition to the auction rules over this time period. Also, there is not a well worked out equilibrium theory for how the rules changes influence equilibrium bidding. Obviously, what we can learn from this simple, descriptive exercise is limited as a result.

Nevertheless, we believe that this systematic examination of the data is valuable. First, a descriptive examination of the bids is often a first step to theorizing about richer models. We note that some of the empirical bidding patterns we observe are not easily rationalized by any existing economic theory. Second, despite its limitations, it may be of use to policy

making. In practice, policy makers design auctions with imperfect knowledge of the strategies that bidders will use and in particular, if they will collude. Simple descriptive evidence, despite its limitations, can serve as a basis for future discussions about auction designs that will take place between regulatory agencies, bidders and academics.

2 Auction Rules

In this section, we describe the rules for bidding in the spectrum auctions. We begin by describing the basic structure of the auction including the structure of the rounds and the activity rules. Next, we describe some modifications of the rules that were made to inhibit collusion, including click box bidding and anonymous bidding.

2.1 Simultaneous Ascending Auction Rules

The FCC spectrum auctions use the simultaneous ascending format. In a typical auction, there are many heterogenous licenses for sale. In a particular round, firms may submit bids on any of the licenses in the auction over the Internet using FCC Auction System. The length of a round is announced in advance. In the 700 MHz auction, for example, rounds lasted 30 minutes. The number of rounds per day is one or two in the early stage but increases to several rounds, for example six (AWS-1) to 14 (700 MHz), in the late stage. At the end of the round, the bids for each license including the identities of the bidders were announced (except for the 700 MHz auction which had anonymous bidding). All bids in round $r + 1$ were required to exceed the high standing bid in round r plus a bid increment. The auction continued until no new bids were received, which lasted up to 6 months in the case of Auction 5. At the end of the final round, the highest bidder on each licenses was awarded the licenses at the price it bid.

In order to keep the auction moving, the FCC imposes activity rules under which the FCC restricts the bidder’s ability to bid in subsequent rounds, called *eligibility*, upon violation. For all four auctions in our data set, the eligibility of a bidder in round $r + 1$ was calculated by the following formula

$$eligibility\ in\ round\ r + 1 = \min(eligibility\ in\ round\ r, \frac{activity\ in\ round\ r}{requirement\ percentage\ in\ r}) \quad (1)$$

A bidder’s activity in round r is equal to the *size* of the licenses for which she is active, that is, she is either the high standing bidder from the previous round or places a bid on the licenses in round r . The size of each license is measured in terms of bidding units which are typically determined by the license’s *Pop-MHz*, the product of the population and the size of

the bandwidth. The *requirement percentage in r* describes the percentage of bidders' eligibility above which each bidder should be active. It is determined by the FCC during the course of an auction. In the C Block (Auction 5) for example, the requirement percentage was .6 in the early rounds and was raised to .8 and then to .95 in later rounds. The auction rules required that a bidder's eligibility was at least as large as the size of the licenses she bid on. If a bidder lost eligibility between rounds, this would limit the set of licenses that she could bid on. These activity rules therefore gave incentives to the bidders with the highest valuations to bid aggressively during the auction.

2.2 Click Box bidding

In auctions 1-15, bidders manually typed their bids into a field which appeared on the bid submission screen on FCC Auction System. Manually typing in the bids created several problems. First, firms could make typing errors, for example, several bidders mistakenly included extra zeros in their bids, inadvertently increasing their bid amounts by a factor of 10! Fortunately, the FCC allowed for bid withdrawals which allowed firms recourse if they inadvertently submitted an incorrect bid. Table 1 summarizes the bid withdrawal rules in our 4 auctions.

Second, and more importantly, manually typing bids allowed firms to engage in code bidding. Cramton and Schwartz (2002) document this behavior in the PCS D, E, and F block auction (Auction 11). Some participants incorporated three-digit market numbers, corresponding to license numbers, into the last digits of some of bids as a means of sending a message to their opponents. For example, the bidder High Plains filed an Emergency Motion for Disqualification, alleging that the bidder Mercury engaged in this anticompetitive behavior. Code bidding could allow bidders to tacitly collude by signalling their most preferred licenses in order to allocate licenses among a cartel without driving up final bids. Also, this strategy could allow bidders to threaten retaliation and hence enforce cartel agreements.

Motivated by these problems, the FCC has used click box bidding since Auction 16. Under click box bidding, bidders are provided with a fixed menu of acceptable bids. In the ASW-1 and Auction 35, for example bidders were offered a menu of 9 bids. The smallest bid was the minimum bid increment plus the highest bid from the previous round. The other additional acceptable bids were determined by multiplying the minimum acceptable bid by successively larger numbers such as 1.1, 1.2, and so on, rounded. The largest bid was typically 80 to 90 percent larger than the standing bid from the previous round depending on the pace of the auction. The rules for click box bidding are also summarized in Table 1.

2.3 Information Disclosure

The FCC used the Full Information Disclosure Procedures in its auction rules until the 700 MHz auction. Under these procedures, the FCC posted the bids placed by each bidder on each license, the identity of the bidder, and the change in each bidder’s eligibility. Economic theory suggests that collusion is easier to enforce firms in markets that are highly transparent because it is easier to punish deviators from collusive arrangements. Anecdotal evidence on retaliating bids are abundant. For example, in the AWS-1 auction, T-Mobile placed a bid only once on Columbia, MO (BEA098) throughout the auction in round 117. It was right after Cavalier Wireless had bid on Hawaii (REAG008) for which T-Mobile had been the standing high bidder since round 55. Cavalier Wireless had been the standing high bidder on Columbia, MO since round 62 until it was challenged by T-Mobile in round 117. While placing a retaliatory bid on Columbia, MO, T-Mobile also placed a bid on Hawaii in round 117 to reclaim it. Cavalier also placed a new bid on Columbia, MO in round 118 to reclaim it and has never placed a bid on Hawaii since then. Bajari and Fox (2007) also provide anecdotes on retaliatory bids in the PCS C block auction.

In response to concerns about potential collusion, the FCC considered limiting the amount of publically available information in the AWS-1 auction. Commissioner Deborah Taylor Tate stated that:

“There has been much debate about whether, and to what extent, tacit collusion, or the opportunity for collusion and other anti-competitive behavior, exists in our current AWS auction rules. Some of the finest scholars have cautioned us that our rules allow—may even invite—such anti-competitive behavior. Economic experts and authors have written articles that support such conclusion and describe how easily bidders can “game” auctions under our current rules. ”

However, the FCC applied the usual full information procedures to the AWS-1 auction the gauge it used to measure of the likely level of competition turned out to be above the pre-specified level.³ In the 700 MHz auction, the FCC used *anonymous bidding*, that is it only posted the standing high bid for each license after each round. The identity of the bidder, the bid amounts other than the standing high bid, and the initial level and changes of each bidder’s eligibility were not revealed until the auction ended.⁴

³The FCC announced that if the ratio of the sum of all the bidders’ initial eligibility, subject to the cap, to the sum of bidding units of all the licenses offered for sale, is equal to or greater than 3, it would conduct AWS-1 under Full Information Disclosure Procedures. The ratio turned out 3.04.

⁴The Public Interest Spectrum Coalition (PISC) along with Verizon and Google agreed with the FCC’s decision. Other bidders, including MetroPCS, argued that anonymous bidding would hurt small firms because

Table 1: Auction Rules

Auction	Minimum opening bids	Click box bidding (Number of acceptable bids) ^a	Anonymous bidding	# of rounds withdrawals allowed	Package bidding	Activity requirement
700Mhz	✓	✓ (1,3) ^b	✓	✓ (2) ^c	✓	80% → 95%
AWS-1	✓	✓ (9)	×	✓ (2)	×	80% → 95%
Auction 35	✓	✓ (9)	×	✓ (2)	×	80% → 90% → 98%
PCS C block	×	×	×	✓ (No Limit)	×	60% → 80% → 95%

^a the number of acceptable bids that the FCC provided for each license per round. ^b For C block licenses, three acceptable bids for individual licenses and one acceptable bid for package bidding. ^c for the licenses subject to package bidding, bidders were allowed to drop non-provisionally winning bids no more than in one round

2.4 Minimum opening bids

For early auctions, including the original three PCS auctions, the minimum opening bid for each license was zero. The lack of a minimum bid may have lead to a strategy called *parking* in which a bidder bid on many licenses that it is not interested in purchasing just to maintain its eligibility. Salant (1997) documented this behavior based on his experience as a consultant for GTE in the PCS A&B block auction. He argues that the GTE bidding team engaged in parking in earlier rounds in order to obfuscate the licenses that GTE most valued and to lower the final prices on these licenses.

There is no evidence or theory which directly suggest that minimum bids are relevant for the study of collusion in these auctions. However, this was a potentially important rule change will will affect the interpretation of our empirical results.

The FCC has also limited the number of bid withdrawals that can be made during an auction since Auction 16. Instances of bid withdrawals following retaliatory bids in Auction 11 were documented in Cramton and Schwartz (2000). The FCC admits that this change was to ensure that bidders do not take advantage of bid withdrawals for strategic advantage.

3 Four Auctions

The data used in this paper comes from 4 auctions, the PCS C block (Auction 5), the C Block Reauction (Auction 35), the AWS-1 auction and the 700 MHz auction. In this section, we briefly describe the items sold in each of these auctions and some summary statistics about the

they rely on the identity of other bidders to provide assurance to their financiers regarding market valuations. Peter Cramton in a letter submitted on the behalf of AT&T also argues that anonymous bidding would hurt efficiency. Alltel proposed that the FCC should at least reveal the changes in each bidder's eligibility after every round.

Table 2: AWS-1 and 700MHz

Auction	Year	No. of licenses offered (sold)	Total Pop-MHz offered (sold) ^a	No. of qualified bidders	Revenue(B)	Net price per Pop-MHz
700Mhz	2008	1099 (1090)	17.708 (14.833)	214	18.958	1.278
AWS-1	2006	1122 (1087)	25.706 (25.539)	168	13.700	0.536
Auction 35	2000	422 (422)	4.029	87	16.957	4.184
PCS C block	1995	493 (493)	7.577	255	10.071	1.330

^a in billions.

winning bids and bidders. In table 2 below, we summarize some key statistics about our 4 auctions including the date of the auctions, the number of licenses, the Pop-MHz, the revenue and the number of bidders.

3.1 PCS C Block

The C block auction was the fifth spectrum auction FCC conducted. The auction was intended to allocate rights to provide a variety of communication services referred to as Broadband PCS for ten years. The FCC allocated spectrum ranging from 1850-1910 MHz and 1930-1990 MHz and divided this 120 MHz of spectrum into six frequency blocks A through F. Blocks A, B and C are 30 megahertz and blocks D, E, and F are 10 MHz each. To define coverage of spectrum licenses in the C block, the FCC used the map of Basic Trading Area (BTA) that divides the US and its territories into 493 areas.

In the C block auction, 255 qualified bidders participated, of which 89 bidders won 493 licenses resulting in \$10.1 billion dollars of revenue. The C block auction started in December 1995 and ended in May 1996 after round 184. The C block was designated for bidders who had revenues for the 3 years preceding the auction less than \$40 million and hence were given a bidding credit of 25%. The C block auction is considered more competitive than the other two broadband PCS auctions. The (population-weighted) average price was \$1.33 per Pop-MHz in the C Block compared to \$0.5 and only \$0.33 per Pop-MHz in the AB and the DEF auctions respectively.⁵ Table 3 summarizes the top 5 bidders in the C Block auction. The largest bidder was NextWave, winning a total of 37.14% of the total Pop-MHz in the auction. The bidders in the auction were quite asymmetric. The 5 largest bidders won 68 percent of the total spectrum. The 5 largest bidders paid \$1.548 per Pop-MHz compared to the remaining bidders who paid \$0.846. This discrepancy is due in part to the fact that the largest bidders were awarded licenses in largest and most affluent U.S. cities.

⁵The average price \$1.33 per MHz pop of the block C auction drops to about \$0.8 per MHz pop after adjusting for the terms of the installment payments available to the small businesses that won C block licenses.

Table 3: Winning Bidders in PCS C Block

Bidder Name	Pop-Mhz ^a	Share of Total Pop-MHz	Net Payment ^b	Net Price per Pop-MHz ^c
NextWave	2.81	37.14%	4.201	1.493
DCR	1.01	13.28%	1.427	1.418
GWI	0.54	7.11%	1.060	1.968
BDPCS	0.46	6.13%	0.874	1.882
Omnipoint	0.39	5.13%	0.509	1.309
Top 5	5.21	68.79%	0.807	1.548
Others	2.36	31.21%	2.001	0.846
Total	7.58		10.072	1.330

^a in billions. ^b in billion dollars. ^c in dollars.

Today, only a handful of C block winners, such as GWI/Metro PCS, are independent carriers. Most of the winning C block bidders merged with larger carriers (forming a large part of licenses held by T-Mobile USA, for example). Other C Block winners sold or defaulted on their licences. Defaulting bidders included BDPCS who won 17 licenses including Seattle, Phoenix, Minneapolis and Denver and Omnipoint who defaulted on 14 licenses it won in the C block. The largest defaulter in the FCC auction history was NextWave. However, NextWave was able to protect some of its licenses in bankruptcy court and eventually sold them to other carriers. For example, NextWave sold its licenses in 23 markets including 20 MHz licenses for New York and Boston to Verizon for \$3.0 billion.

3.2 Auction 35

The returned or canceled PCS licenses were reauctioned via several auctions. Auction No. 35 offered licenses in the C block and the F block, originally sold in Auction No. 5 (PCS C block) and Auction No. 11 (PCS D, E, and F blocks) including licenses reclaimed from bankrupt NextWave. Auction 35 began on 12/12/2000 and closed on 1/26/2001. 87 bidders participated and 35 bidders won 422 licenses after 101 rounds over 24 days. Small businesses were given a bidding credit of 15% or 25% on C and F block licenses won in Auction No. 35. Certain C and F block licenses were only available to entrepreneurs in “closed” bidding.⁶ Table

⁶In order to qualify as an “entrepreneur”, an applicant, including attributable investors and affiliates, must have had gross revenue of less than \$125 million in each of the last two years and must have less than \$500 million in total assets. A law suit against AT&T was filed after the auction for using a bidding front Alaska Wireless to bid on licenses reserved for small and minority-owned businesses and acquire bidding credits intended only for those businesses. Cramton and et al (2008) studies the effect of having AT&T in the competition for licenses set aside designated entities. They conclude AT&T’s presence caused an increase in price of roughly \$1.15 per

Table 4: Major winning bidders in Auction 35

Bidder Name	Pop-Mhz ^a	Share of Total Pop-MHz	Net Payment ^b	(Net) Price per Pop-MHz ^c
Cellco Partnership, d/b/a Verizon Wireless	1.52	37.67%	8.78	5.79 (5.79)
Salmon PCS, LLC	0.74	18.37%	2.35	3.93 (3.17)
Alaska Native Wireless, L.L.C.	0.65	16.11%	2.89	4.56 (4.46)
Leap Wireless International, Inc.	0.20	4.97%	0.35	1.92 (1.75)
DCC PCS, Inc.	0.18	4.49%	0.55	3.02 (3.02)
sum of top 5	3.29	81.62%	14.92	4.74 (4.54)
others	0.74	18.38%	1.94	2.72 (2.62)
total	4.03		16.86	4.37 (4.18)

^a in billons. ^b in billion dollars. ^c in dollars.

4 summarizes the bids of the top 5 bidders in the auction. As in the C block, the bidders were quite asymmetric with the top 5 bidders winning 81% of the total Pop-MHz. Note that the price of Pop-MHz was on average \$4.37 (\$4.18 in net), a substantial increase over the original auction prices for these licenses \$2.01 (\$1.51 in net) without adjusting for inflation. Bids for the majority of licenses at Auction 35 were eventually canceled as NextWave protected its licenses under federal bankruptcy law.

3.3 AWS-1 and 700 MHz

The ASW auction was held in 2006 and offered 1122 licenses for sale, of which 1087 were sold. The licenses in this auction could be used for a variety of wireless services including Third Generation (“3G”) mobile broadband and advanced wireless services for voice and data. The FCC allocated spectrum ranging from 1710-1755 MHz and 2110-2155 MHz for AWS-1 and divided this 80 MHz of spectrum into six frequency blocks A through F. Blocks A, B and F were 20 MHz and blocks C, D and E are 10 MHz. To define coverage of spectrum licenses in Block A, the FCC used maps of Cellular Market Area (CMA) which divides the US and its territories into 734 areas. For blocks other than A, Basic Economic Area and Regional Economic Area Grouping are used to define coverage of spectrum licenses.

The 700 MHz auction began on 1/24/2008 and ended on 3/18/2008. There were 1099 licenses for sale of which 1090 eventually sold. In the auction, 214 bidders were qualified to participate of which 101 bidders won 1090 licenses. Ultimately, 9 licenses, including the nationwide D block license, were unsold. The 700 MHz auction offered licenses to use 698-806 MHz band which is currently owned by broadcasters for analog television which will be turned

MHz Pop, or 58% of the final prices of closed licenses.

Table 5: Winning Bidders in AWS-1 and 700MHz

AWS-1						
	T-Mobile	SpectrumCo	Verizon	Cingular	Top 4	Others
Pop-MHz(B)	6.64	5.27	3.84	2.44	18.18	7.36
Net payment(B)	4.18	2.38	2.81	1.33	10.70	3.00
Price per Pop-MHz	0.63	0.45	0.73	0.55	0.59	0.41
Total Purchase ^a	25.83%	20.49%	14.94%	9.48%	70.74%	29.26%
700MHz						
	Verizon	AT&T	Frontier		Top 3	Others
Pop-MHz(B)	9.36	2.11	1.30		11.92	2.91
Net payment(B)	8.51	6.64	0.712		16.72	2.25
Price per Pop-MHz	1.10	3.15	0.55		1.40	0.77
Total Purchase ^a	57.36%	14.22%	8.79%		80.37%	19.65%

^a relative to the total Pop-MHz sold.

over to the government in 2009. These lower frequencies travel farther and penetrate solids better compared to higher frequencies. Those properties of lower frequencies make them more cost efficient for uses for wireless service. According to the Congressional Research Service, one access point in a 700MHz network can cover the same area as four access points in a 2.4 GHz network. Some industry analysts argued that this auction could transform the wireless broadband landscape in the US as a result.

Table 5 shows the four biggest winners in the AWS-1. The four biggest winners accounted for 71% of the total units of Pop-MHz sold and 78% of the total revenue. T-mobile was the biggest bidder accounting for 25.99% of the total amount of Pop-MHz sold. The table also shows the three biggest winners in the 700MHz auction. Verizon purchased 57% of the total Pop-MHz sold including the 8 C block licenses which are subject to the open access requirements.

4 Overview of Bidding Behavior

In this section, we provide a basic description of how the bids evolve over the course of the auction. In particular, we describe how bidder eligibility and the number of remaining bidders evolves from early to late rounds. This allows us to graphically study the “speed” of the auction. We shall also discuss how the speed of the auction is influenced by reserve prices.

4.1 Eligibility

Figure 1 graphs changes of bidders’ eligibility in our four auctions. The vertical axis is defined at the ratio of two terms. The numerator is the sum of all bidder’s eligibility. The denom-

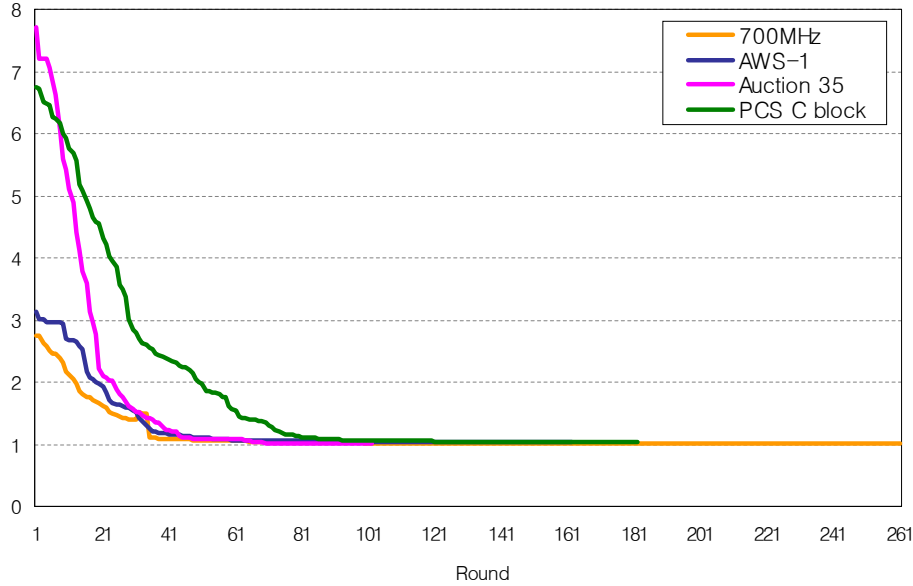


Figure 1: Changes in eligibility ratio over rounds

inator is the number of bidding units required to purchase all of the licenses in the auction. The horizontal axis in this figure is the round in the auction. Notice that bidder eligibility, as measured by the vertical axis declines monotonically over the course of the auction and eventually converges to one. Eligibility summed over all bidders will decline as a consequence of equation (1). As the rounds progress, the bids will increase and some bidders will no longer continue to bid on a particular license. This decision not to bid will result in a loss of eligibility of a subset of the bidders. This process will continue until, by the rules of the auction, there is just enough eligibility for the remaining bidders to purchase the available licenses.

Recall from Table 1 that minimum bids were not used in the PCS C block. Auction 35 had minimum bids, but these were quite low compared to the final prices. The sum of the minimum bids divided by the sum of the final prices was 0.026. In the AWS-1 and 700 MHz auctions, the reserve prices were considerably higher compared to the final prices. The analogous sum in these auctions was 0.084 and 0.104. Figure 1 suggests that the level of the minimum bids significantly influenced the pace of the auction and participation, and could help explain why the sum of bidders' initial eligibility was lower in AWS-1 and the 700 MHz auctions than in the two earlier auctions.

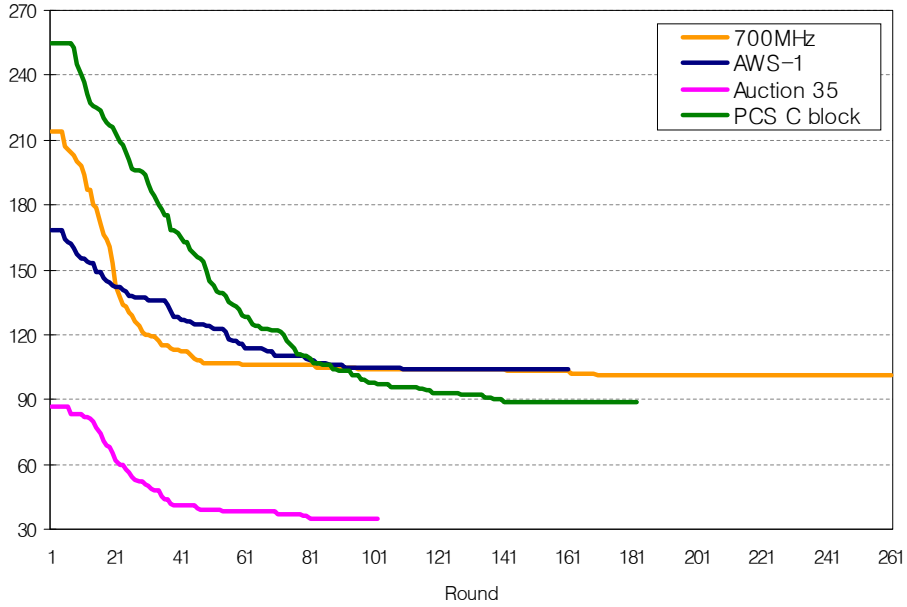


Figure 2: Number of Qualified bidders

4.2 Number of Bidders

Figure 2 graphs the number of bidders in our 4 auctions. The vertical access is the number of active bidders remaining in the auction and the horizontal axis is the round of the auction. The number of active bidders decreases monotonically over time as bidder eligibility decreases. As the rounds in an auction increase, the standing prices on each of the licenses will go up. A subset of the bidders will choose not to bid at the higher standing prices and will therefore lose eligibility as illustrated in 1. As their eligibility drops towards zero, such bidders will be forced to leave the auction as illustrated in 2.

Analogous to figure 2, the reserve prices seem to have a strong influence on bidding activity early in the auction. In the PCS C block and Auction 35 where reserve prices were low, more bidders participated with large eligibility, but the percentage decrease in bidders is much larger than in the later AWS-1 and 700 MHz auctions.

Obviously, we are not able to draw a direct causal link between the reserve prices and the evolution of eligibility and the number of bidders over the course of the auction. We are not able to control for all factors which influence bidding decisions in such a simple figure. Nonetheless, the differences in the reserve prices is certainly a leading explanation for differences in the speed of the various auctions.

5 Collusive Bidding

In this final section, we study the relationship between the rules of the auction and the frequency of potentially “collusive” bidding strategies. As we discussed in the introduction, it is not possible to directly test for tacit collusion using simple, descriptive methods for two reasons. First, economic theory does not give clear guidance on how to distinguish collusive from non-collusive strategies in many simple models. Spectrum auctions are extremely complicated, making it even more difficult to theoretically characterize collusive from non-collusive bidding. Second, there is the problem of omitted variables. The characteristics of the licenses and the industry is changing across our sample in ways that we cannot directly control for in our analysis. The latent factors certainly explain some part of bidding behavior and we are not taking account of them in our analysis.

Despite these limitations and with these caveats, we still believe it is useful to examine how bidding differs across auctions. Simple, descriptive analysis is often a first step towards better theoretical and econometric models. Also, policy makers cannot wait until definitive theoretical or empirical work in economics is completed, if such work is ever available. In applied policy work, decisions must be made with incomplete and imperfect information. Simple, descriptive evidence is often combined with a broader understanding of the industry, economic theory and public feedback to determine future changes to the auction mechanism.

5.1 Straightforward Bidding

The concept of straightforward bidding is discussed in Milgrom (2000, 2004). Bidders bid straightforwardly if, at each round, they place the minimum bid on the additional licenses they would wish to acquire if the auction were to end after the round, but are not provisionally winning at the moment. Straightforward bidding is feasible if and only if licenses are substitutes.⁷ Straightforward bidding has played an important role in theoretical models of spectrum auctions. For example, Milgrom (2000) demonstrates that if licenses are substitutes and bidders bid straightforwardly, then the final allocation of licenses will resemble a competitive equilibrium allocation. The straightforward bidding behavior does not permit collusive behavior.

We begin therefore by exploring the frequency of straightforward bids across our four auctions. Two obvious cases of non-straightforward bids are jump bids and self bumping bids. We define a jump bid as a bid that is greater than 5 percent of the Minimum Acceptable Bid

⁷There are several empirical studies on the “non-substitutability” among licenses due to existence of synergy effects. See Ausubel, Cramton, McAfee and McMillan (1997), Moreton and Spiller (1998) and Bajari and Fox (2007).

Table 6: Jump Bids

	PCS-C Block	Auction 35	AWS-1	700 MHz
All bids placed	27,763	19,798	16,197	36,418
Bids= MAB	14236(51.3%)	19575(98.9%)	15957(98.5%)	36408(99.97%)
Bids> MAB	13527(48.7%)	223(1.1%)	240(1.5%)	10(0.03%)
Bids> 5% of MAB	1193(4.3%)	203(1.0%)	186(1.1%)	10(0.03%)

Table 7: Self-bumping bids

Auction	PCS-C Block	Auction 35	AWS-1	700 MHz
Total bids from round 2	27,783	18,893	15,466	34,569
Self-bumping bids	567(2.04%)	43(0.23%)	12(0.08%)	265(0.77%)

(MAB). We define a self bumping bid as a case in which the provisionally winning bidder increases her own bid in the auction.

Table 6 presents frequencies of jump bids in the four auctions and Table 7 presents frequencies of self-bumping bids.

The results of the tables are quite striking. In the PCS C Block only half of the bids are equal to the MAB compared to nearly 99 percent of the bids in the other three auctions. Also, 2 percent of the bids are self bumping in the C block compared to less than one percent in the other auctions. Recall that the 700 MHz had anonymous bidding and click box bidding. AWS-1 and Auction 35 both had click box bidding. As we discussed in the introduction, click box bidding restricts the set of available bids and therefore possibly the scope to signal or intimidate other bidders in the auction. The C Block had neither of these features and economic theory suggests that there may have been greater scope for colluding with other bidders. This is one interpretation of Tables 6 and 7. Of course, the C Block had a much larger number of bidders, many of whom were small. Also, the C Block had no minimum bids. These or other factors could also be responsible for the part of the differences across Tables 6 and 7.

5.2 Additional tests of straightforward bidding

In this subsection, we describe another test of straightforward bidding. Let i denote license and r denote a round. Let $S_{i,r}$ denote the package of licenses for which bidder i is the standing high bidder at the start of round r or that bidder i places a bid on during round r . In other words, $S_{i,r}$ is the set of licenses on which bidder i was active in round r . Assume that bidder i has a quasi-linear utility function and let $v_i(S_{i,r})$ denote i 's dollar valuation for the licenses in $S_{i,r}$. Given a license l in $S_{i,r}$, let $p_{i,r}^l$ be equal to the minimum acceptable bid on license l if i is not the high standing bidder. If i is the current high standing bidder at the start of

round r , let $p_{i,r}^l$ denote i 's bid from the previous round. Milgrom (2000) refers to this as the personalized price of license l for bidder i in round r . Define $P_{i,r}(S_{i,t}) = \sum_{l \in S_{i,t}} p_{i,r}^l$. This is the sum of personalized bids for licenses on which i is active.

Suppose bidder i bids straightforwardly throughout the auction and there is no budget constraint. Let r and r' be any two rounds in the auction in which bidder i bid. Then, revealed preference implies that

$$v_i(S_{i,r}) - P_{i,r}(S_{i,r}) \geq v_i(S_{i,r'}) - P_{i,r}(S_{i,r'}) \quad (2)$$

$$v_i(S_{i,r}) - P_{i,r'}(S_{i,r}) \leq v_i(S_{i,r'}) - P_{i,r'}(S_{i,r'}) \quad (3)$$

In (2) the term $v_i(S_{i,r}) - P_{i,r}(S_{i,r})$ is i 's value for $S_{i,r}$ minus the personalized prices that i faces $S_{i,r}$. This difference would be i 's surplus if the auction closed at round r . The term $v_i(S_{i,r'}) - P_{i,r}(S_{i,r'})$ is the analogous term from $S_{i,r'}$, the items that i bid on in round r' . In words, this means that at personalized prices in round r , $S_{i,r}$ is revealed preferred to $S_{i,r'}$. The second inequality is the analogous expression for round r' .

Adding these two inequalities together yields that

$$P_{i,r}(S_{i,r}) - P_{i,r}(S_{i,r'}) \leq P_{i,r'}(S_{i,r}) - P_{i,r'}(S_{i,r'}). \quad (4)$$

Note that the inequality (4) does not involve the valuations $v_i(S_{i,r})$ and $v_i(S_{i,r'})$ which are not directly observed by the economist. Instead, it only involves the personalized prices of the package of licenses the bidder was active on which we can observe given the bids in the auction. The inequality (4) is therefore a testable implication of straightforward bidding.

Next, let $I(r)$ denote the set of remaining bidders in round r . Define

$$\phi(r) = \frac{\sum_{i \in I(r)} 1(P_{i,r}(S_{i,r}) - P_{i,r}(S_{i,r-1}) \leq P_{i,r-1}(S_{i,r}) - P_{i,r-1}(S_{i,r-1})) 1(S_{i,r} \neq S_{i,r-1})}{\sum_{i \in I(r)} 1(S_{i,r} \neq S_{i,r-1})}$$

Straightforward bidding implies that $\phi(r) = 1$ for all rounds r . $\phi(r)$ always lies between 0 and 1. It can be interpreted as a measure of the frequency with which the revealed preference inequalities (2) and (3) implied by straightforward bidding are violated between two adjacent rounds r and $r - 1$. Next, we display $\phi(r)$ for all rounds in the four auctions in our data set.

Figure 3 shows a very striking result. As the auction rules evolved over time, there was a high frequency of rounds in which $\phi(r)$ was close to one. In the C Block auction, $\phi(r)$ was significantly less than one in almost all rounds before round 93 of the 183 round auction. In the 700 MHz auction, $\phi(r)$ is equal to one in most rounds larger than 33. The amount and length of non-straightforward bidding in auction 35 and the AWS-1 lie between these two extreme

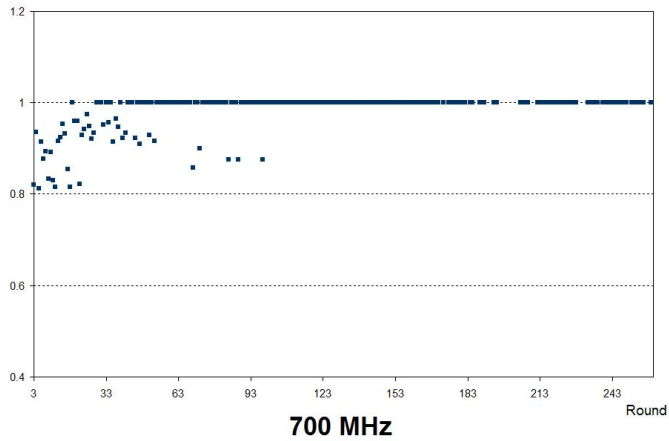
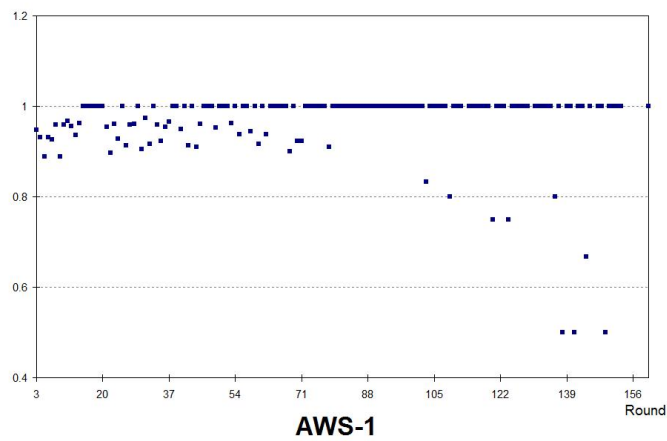
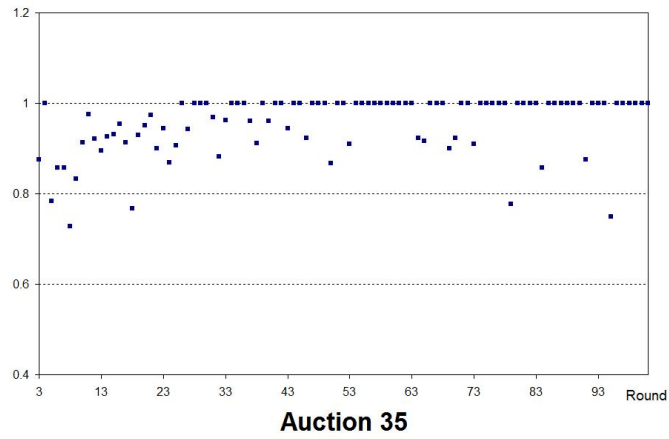
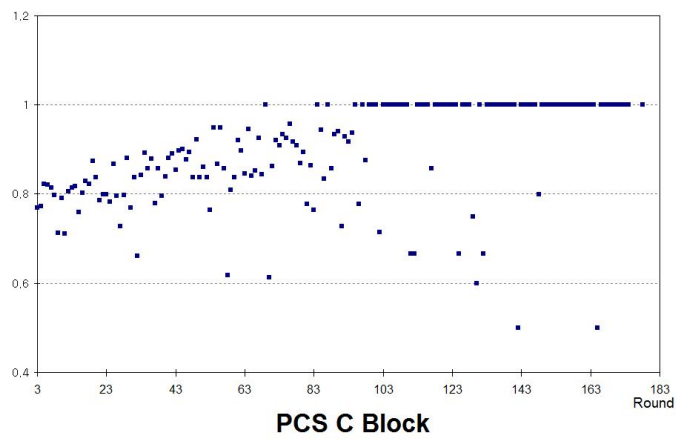


Figure 3: Revealed Preference with Straightforward Bidding

points. One interpretation of these graphs is that as the FCC introduced click box and then anonymous bidding, bids became increasingly straightforward and hence non-collusive.

Obviously, this is not the only interpretation. First, the 700 MHz auction had much larger firms than the C Block that were bidding at a much later point in time. Therefore the equilibrium behavior could differ in ways that we have failed to control for in these figures. Second, it is possible that bidders found alternative ways to tacitly collude that were not as brazen as the examples discussed in Cramton and Schwartz (2002). A final interpretation is that no collusion occurred and that our diagnostics for collusion and economic theories of bidding are woefully inadequate.

It is not possible to rule out any of these alternatives given what is discussed above. However, the differences in bidding patterns across the auctions are quite striking and do seem consistent with an interpretation that bidding has become more straightforward as the rules have evolved.

5.3 Comparison: AWS-1 vs. 700 MHz

Finally, we perform an exercise similar to Cramton and Schwartz (2002) and search for evidence of retaliatory bids. We say that bidder j bumped bidder i from license l if j replaced i as the high bidder in a round. The idea behind retaliatory bidding is that once bumped, i will run up the bid on a license l' . Bidder i 's motive for bidding on l' is to discourage j from continuing to bid on l .

For a bid to be a retaliatory bid, we require a clear possible motive. The criteria we consider are:

- i) The challenged bidder j bumped the retaliating bidder i from some license l in the two rounds prior to round r .
- ii) Bidder i is not interested in winning l' . That is, the retaliating bidder i has never submitted a bid for l' that is not a retaliatory bid in a round prior to r in which he bumped j .
- iii) Bidder j 's interest in l' should be clear to bidder i . Bidder j submitted bids on l' for at least twice in prior rounds or j has been a standing high bidder for the previous ten rounds.
- iv) Bidder i 's signal should be clear to j : there is only one j and one l' that meets i) to iii).

Obviously, there are many ways to define a retaliatory bid. Conditions i) through iv) contain features that we believe are intuitively sensible. In addition, we will also consider the

Table 8: Retaliatory bids in AWS-1 and 700MHz

	AWS-1		700 MHz	
i) to iii)	317	bouts	275	bout
i) to iv)	136	bouts	78	bouts
i) to v)	103	bouts	67	bouts
i) to vi)	38	bouts	17	bouts

following criteria in order to be conservative in our definition of retaliation. In particular, we eliminate a bid returned by the above conditions if

v) The retaliating bidder did not consistently adhere to a punishment strategy : although j keeps bidding on l , i stops bidding on l'

vi) There is a round after round r in which i bid on l' and j did not bid on l

Table 8 summarizes the number of bouts of retaliatory bidding were observed in the AWS-1 and 700 MHz auctions. A bout is a set of bids with distinctive retaliator(i), retaliatee(j), contested license(l), a license used as a messenger (l'). We count the bouts using various criterion in order to exam the sensitivity of our conclusions to alternative definitions of retaliation.

Recall that the 700 MHz auction had anonymous bidding while AWS-1 did not. Obviously, retaliatory bidding is more difficult if there is anonymous bidding since bidder i may have no idea if he is retaliating against the correct bidder! Also, anonymity makes it more difficult for i to signal her intentions to j by bidding on l' . Table 8 suggests that there were fewer retaliatory bids in the 700 MHz auction than in the AWS-1 auction as a result of hiding bidder identities. Obviously, as we discussed in the previous sections, we cannot consider this as conclusive evidence of the effect of anonymous bidding on collusion.

6 Conclusion

A long literature in theoretical and empirical economics suggest that collusion can greatly reduce economic efficiency. Economic theory predicts that one of the main challenges a cartel faces is to monitor and enforce cartel agreement. Auctions are highly transparent economic mechanisms. In the PCS C Block, for example, bid amounts, bidder identities and bidder eligibility were publicly observed during the course of the auction. While auctions have many advantages, a potential disadvantage is that this transparency facilitates collusion. We concur with Marshall and Marx (2007) who have argued that collusion is of first order important in auction design.

Since the introduction of spectrum auctions in 1994, the FCC has introduced rule changes including click box and anonymous bidding that potentially make collusion more difficult. Click box bidding makes it harder for bidders to directly signal each other. Anonymous bidding disguises the identity of bidders during the auction, making it difficult, and perhaps impossible, for the cartel to use the bids to monitor and enforce collusive agreements.

We examined bids from four of the largest spectrum auctions: the PCS C Block, Auction 35, AWS-1 and the 700 MHz auction. We searched for evidence of three types of collusive strategies: the frequency of jump bids, non-straightforward bids and retaliatory bids. The evidence suggests that the rule changes introduced by the FCC have made it more difficult for bidders to collude. In the 700 MHz auction for example, there were fewer retaliatory bids, jump bids and more straightforward bidding than in earlier auctions. As we have discussed in the text, there is no fool proof procedure for detecting collusion short of a wiretap or other physical evidence of explicit cartel agreements. The results we presented are only statistical and do not constitute proof of tacit or explicit collusion.

At a minimum, we hope that our research will encourage future theorizing and econometric modeling of the rich dynamics in spectrum auctions. In our opinion, these dynamics are a very important, if puzzling, component of bidder behavior and have not been adequately explored in the literature. Improved auction design, including preventing tacit collusion, could benefit greatly from an enhanced understanding of the dynamics of bidder behavior.

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