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 that can be submitted during a particular round. Economic theory suggests that tacit collusion may be more difficult as a result. We examine this proposition using data from four auctions: the PCS-C Block, the PCS-C&F Block Reauction, 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 suggest that these rule changes have limited firms' ability to tacitly collude.

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1. Introduction

Since 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 who values the item most highly will win the auction. Therefore, the auction results in an efficient allocation. Second, auctions generate higher revenues than do lotteries or administrative hearings by making firms pay for the right to own licenses. The recent 700 MHz auction generated 19.1 billion dollars in revenues. Finally, auctions have clear and transparent rules for awarding licenses. This clarity minimizes the possibility for corruption and economizes on inefficient influence costs from the act of persuading administrative boards.[1]

Over the past decade, a large theoretical literature on spectrum auctions has emerged (See Milgrom (2004) for an excellent survey). An important, but often overlooked, aspect of auction design is mitigating collusion among bidders (see Marshall and Marx (forthcoming)). 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 where publicly observable during the course of the auction. Avery (1998) demonstrated that jump bids may soften competition in ascending auctions, thus serving as a tool to signal bidder valuations. Brusco and Lopomo (2002) characterize collusive equilibria that can be sustained due to bidders' ability to observe their opponents' deviation from collusive behavior.[2]

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[1] Kwerel and Rosston (2000) provides an excellent summary on the FCC's decision on the auction design as well as some issues that have arisen in early auctions.

[2] Ausubel et al. (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.

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.[3] 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%. Also, click box bidding makes "code bidding" more difficult. In Auction 11 (the PCS D, E, and F block auction), bidders were allowed to freely choose their bid. In many cases, their bids included 7 or more figures and the trailing digits were used to communicate their intentions to rivals. For example, if a bidder intended to vigorously defend license 451, that bidder might include 451 as the last 3 digits at the end of its bids. Obviously, this is mechanically impossible when using click box bidding.

A second rule change is anonymous bidding, introduced in the 700 MHz auction. In anonymous bidding, the identities of the bidders are no longer publicly 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 Green 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 involves increases in minimum opening bids. Large minimum opening bids increase the risk of a financial loss when a participant bids on licenses which it does not ultimately intend to win. One example of such behavior is called "parking," which refers to the behavior of delaying until later rounds the bidding for licenses that a participant desires in order to soften competition over those licenses.

In this paper, we examine bids from four 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, the PCS-C&F Block Reauction, the Advanced Wireless Service auction and the 700 MHz auction. These auctions are the largest in terms of revenue generated and they all took place between 1994 and 2008.[4] As a result of this time span, we see the FCC's use of a variety of different rules that 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. Apart from changes in the auction rules, the items sold and the size of the cellular industry also varied over this time period. Also, there is not a well worked out equilibrium theory for how the rules changes should 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, our analysis 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 are likely to 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 over the Internet on any of the licenses in the auction, using the FCC Auction System. The length of a round is announced in advance. In the 700 MHz auction, for example, rounds lasted 30 min. The number of rounds per day is one or two in the early stage but increases to several rounds in late stages. For example, there were six rounds per day in the final stage of the AWS-1 auction and 14 in the 700 MHz auction. At the end of the round, the bids for each license, including the identities of the bidders, are announced (except for the 700 MHz auction, which had anonymous bidding). All bids in round $r + 1$ were required to exceed the standing high bid in round r by a bid increment. The auction continues until no new bids are received, which in the case of Auction 5, extended the auction process to nearly 6 months. At the end of the final round, the highest bidder on each individual license is awarded the license at the price it bid.

In order to control the pace of auctions, the FCC adopted an activity rule. The activity rule requires a minimum level of activity in every round for a bidder to maintain its *eligibility* to bid in subsequent rounds. A bidder's *activity* in round r is equal to the *size* of the licenses for which it is

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active; the bidder is the highest bidder from the previous round or places a bid on the license in round *r*. The size of each license is measured in terms of *bidding units*, which are determined by the license's MHz-pop, defined as the product of the population and the size of the bandwidth. A bidder's eligibility determines the maximum level of activity it can engage in. The bidder must purchase an initial level of eligibility at a negligible cost prior to the beginning of an auction.[5]

For all four auctions in our data set, the eligibility of a bidder in round *r* + 1 was calculated by the following formula:

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

The *requirement percentage in r* describes the percentage of bidders' eligibility above which each bidder should be active, and 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. If a bidder lost eligibility, that would limit the set of licenses that it could bid on. These activity rules therefore gave an incentive the bidders to bid aggressively during the auction.

2.2. Click box bidding

In Auctions 1–15, bidders manually typed their bids into a field that appeared on the bid submission screen on the 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 four auctions.

Second, and more importantly, manual typing of 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 AWS-1 and the PCS-C&F Block Reauction, 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, and then rounding to a significant digit. Depending on the pace of the auction, the largest acceptable bid was typically 80–90 percent larger than the standing bid from the previous round. The rules for click box bidding are also summarized in Table 1.

2.3. Information disclosure

Until the 700 MHz auction, the FCC used the Full Information Disclosure Procedures in its auction rules. Under these procedures, the FCC posted each bid 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 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 in round 117 on Columbia, MO (BEA098). This occurred immediately 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 then placed a new bid on Columbia, MO in round 118 to reclaim the license and never again placed a bid on Hawaii. 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 publicly available information in the AWS-1 auction.[6] 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."[7]

However, the FCC applied the usual full information procedures to the AWS-1 auction because the gauge it used to measure of the likely level of competition turned out to be above the pre-specified level.[8] In the 700 MHz auction,

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[5] The price of initial eligibility per MHz-pop was $0.03 for licenses in rural areas and $0.05 for licenses in urban areas in both the AWS-1 auction and the 700 MHz auction.

[6] See Marx (2006) for some background on the FCC's motivation for considering anonymous bidding in the AWS-1 auction.

[7] Statement of Commissioner Deborah Tayer Tate in response to Public Notice (FCC 06-47).

[8] The 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.

Table 1
Auction rules.

Auction	Minimum opening bids[a]	Click box bidding (Number of acceptable bids)[b]	Anonymous bidding	# of rounds withdrawals allowed	Activity requirement
700 MHz	✔ (10.4%)	✔ (1,3)[c]	✔	✔ (2)[d]	80% → 95%
AWS-1	✔ (8.4%)	✔ (9)	×	✔ (2)	80% → 95%
C&F Block Reauction	✔ (2.6%)	✔ (9)	×	✔ (2)	80% → 90% → 98%
PCS-C Block	×	×	×	✔ (No limit)	60% → 80% → 95%

[a] The number shown in parentheses is the ratio of the sum of minimum opening bids to the sum of final prices.
[b] The number of acceptable bids that the FCC provided for each license per round.
[c] For C block licenses, three acceptable bids for individual licenses and one acceptable bid for package bidding.
[d] For the licenses subject to package bidding, bidders were allowed to drop non-provisionally winning bids in no more than one round.

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.[9]

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 encouraged parking strategies in which a participant bids on many licenses that the participant is not interested in winning just to maintain 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 that directly suggests that minimum opening bids are relevant to the study of collusion in FCC spectrum auctions. However, introduction of minimum opening bids was a potentially important rule change that might have limited collusion. Higher minimum opening bids give the bidders fewer rounds to work out a split of the licenses before prices reach their willingness-to-pay.

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), and Weber (1997) discusses the strategic use of bid withdrawals in the PCS A&B block (Auction 4) auction. The FCC admits that this change was to ensure that bidders do not use bid withdrawals for strategic advantage.[10]

3. Four auctions

The data used in this paper comes from four auctions: the PCS-C Block (Auction 5), the PCS-C&F Block Reauction (Auction 35), the AWS-1 (Auction 66) and the 700 MHz (Auction 73). In this section, we briefly describe the items sold in each of these auctions and some summary statistics about the winning bids and bidders. In Table 2, we summarize some key statistics about these 4 auctions including the date when each was held, the number of licenses, the MHz-pop, the revenue and the number of bidders.

3.1. Overview of the four auctions

3.1.1. PCS-C Block

The PCS-C Block was the fifth FCC spectrum auction. This auction was intended to allocate rights to provide a variety of communication services referred to as Broadband PCS for a ten-year term plus a renewal expectancy. The FCC allocated spectrum in the 1850–1910 MHz and 1930-1990 MHz bands and divided this 120 MHz of spectrum into six frequency blocks labeled A through F. Blocks A, B and C are 30 MHz and blocks D, E, and F are 10 MHz each. To define coverage of spectrum licenses in the C block, the FCC used Basic Trading Areas (BTA's) that divide the US and its territories into 493 areas.

In the C block auction, 255 qualified bidders participated, of which 89 bidders won the 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 with an average annual revenue of less than 40 billion dollars in the 3 years preceding the auction. These small bidders were given a bidding credit, set at 25%. The C block auction is considered more competitive than the other two broadband PCS auctions. The average price per MHz-pop was $1.33 in the C block, which is larger in comparison to $0.50 in the A and B blocks and only $0.33 in the D, E and F blocks.[11] 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 MHz-pop in the auction. The bidders in the auction were quite asymmetric. The 5 largest bidders won 68% of the total spectrum. These 5 largest

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[9] The 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 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.
[10] Public Notice (FCC 06-47), paragraph 233.

[11] The 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 2
Auction results.

Auction	Year	No. of licenses offered (sold)	Total MHz-pop offered (sold)[a]	No. of qualified bidders	Revenue (B)	Net price per MHz-pop
700 MHz	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
C&F Block Reauction	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.

Table 3
Winning bidders in PCS-C Block.

Bidder name	MHz-pop[a]	Share of total MHz-pop (%)	Net due[b]	Net price per MHz-pop[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.

bidders paid $1.548 per MHz-pop compared to the remaining bidders, who paid $0.846. This discrepancy is due in part to the fact that the largest bidders bought licenses in the most populated U.S. cities.

Today, only a handful of C block winners, such as GWI/Metro PCS, are independent carriers. Most of the winning C block bidders later 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. Prominent examples of defaulting bidders include BDPCS which returned 17 licenses to the FCC, including Seattle, Phoenix and Minneapolis, and Omnipoint which returned 14 licenses. 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.

3.1.2. PCS-C&F Block Reauction

The returned or canceled PCS licenses were later reauctioned. The PCS-C&F Block Reauction offered licenses in the C block and the F block, originally sold in Auction 5 (PCS-C Block) and Auction 11 (PCS D, E, and F blocks) including licenses reclaimed from bankrupt NextWave. The PCS-C&F Block Reauction began in December, 2000 and closed in January, 2001. A total of 87 bidders participated and 35 of them won 422 licenses after 101 rounds extending over 24 days. Small businesses were given a bidding credit of 15% or 25% on C&F Block licenses won in this auction. Certain C&F Block licenses were only available to entrepreneurs in "closed" bidding.[12] Table 4 summarizes the bids of the top 5 bidders in this auction. As in the PCS-C Block auction, the bidders were quite asymmetric, with the top 5 bidders winning 81% of the total MHz-pop. Note that the price per MHz-pop was $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 in the PCS-C&F Block Reauction were eventually canceled as NextWave protected its licenses under federal bankruptcy law.

3.1.3. AWS-1 and 700 MHz

The AWS auction was held from August to September of 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 in the 1710–1755 MHz and 2110–2155 MHz band for AWS-1 and divided this 90 MHz of spectrum into six frequency blocks, A through F. Blocks A, B and F were 20 MHz and

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[12] In 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 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 MHz Pop, or 58% of the final prices of closed licenses.

Table 4
Major winning bidders in PCS-C&F Block Reauction.

Bidder name	MHz-pop[a]	Share of total MHz-pop (%)	Net due[b]	(Net) Price per MHz-pop[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, LLC	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 billions.
[b] In billion dollars.
[c] In dollars.

Table 5
Winning bidders in AWS-1 and 700 MHz.

	T-Mobile	SpectrumCo	Verizon	Cingular	Top 4	Others
AWS-1						
MHz-pop(B)	6.64	5.27	3.84	2.44	18.18	7.36
Net due(B)	4.18	2.38	2.81	1.33	10.70	3.00
Price per MHz-pop	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%
	Verizon	AT&T	Frontier		Top 3	Others
700 MHz						
MHz-pop(B)	9.36	2.11	1.30		11.92	2.91
Net due(B)	8.51	6.64	0.712		16.72	2.25
Price per MHz-pop	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 MHz-pop sold.

blocks C, D and E are 10 MHz. To define coverage of spectrum licenses in block A, the FCC used Cellular Market Areas (CMA's) that divide the US and its territories into 734 areas. For the other blocks, the FCC used Basic Economic Areas (BEA's) and Regional Economic Area Groupings (REAG's) to define the geographic areas.

The 700 MHz auction was held in January through March of 2008. There were 1099 licenses for sale, of which 1090 sold. In the auction, 214 bidders qualified to participate and 101 bidders won 1090 licenses. Ultimately, 9 licenses, including the nationwide D block license, were unsold. The 700 MHz auction offered licenses in the 698–806 MHz band that is currently used by broadcasters for analog television and will be turned 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 wireless service. According to the Congressional Research Service, one access point in a 700 MHz 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.

Table 5 shows the four biggest winners in the AWS-1. These participants accounted for 71% of the total units of MHz-pop sold and 78% of the total revenue. T-Mobile was the biggest bidder, accounting for 25.99% of the total amount of MHz-pop sold. Table 5 also shows the three biggest winners in the 700 MHz auction. Verizon purchased 57% of the total MHz-pop sold including the 8C block licenses that are subject to an open platform restriction.[13]

3.2. Overview of bidding dynamics

In this section, we study the "speed" of each auction. In particular, we describe and depict graphically how bidder eligibility and the number of remaining bidders evolved from early to late rounds. We shall also discuss how the speed of the auction is influenced by reserve prices.

3.2.1. Eligibility
Fig. 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 measured by bidding units. The denominator is the

[13] The C block licenses, which were initially offered subject to an open platform restriction, were to be reauctioned without the restriction if the reserve price for the block had not been met. Google's bid for the licenses above the reserve price ensured no reauction, and Verizon eventually outbid Google. We feel that this reauction rule is not directly related to collusive behavior we consider although it may have important implications on efficiency. The effect of the rule on other bidders' equilibrium behavior in the presence of a bidder who benefits from the restriction (Google in the 700 MHz auction) is analyzed by Brusco et al. (2009). They further propose a mechanism that improves upon contingent reauctions both in terms of efficiency and seller revenue in Brusco et al. (2008).
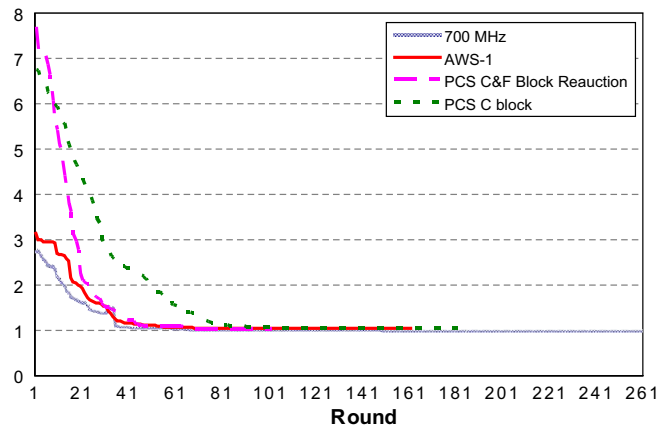
Fig. 1. Changes in eligibility ratio over rounds.

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 the ratio, as measured by the vertical axis declines monotonically over the course of the auction and eventually converges to one. Given that the eligibility ratio will be equal to 1 when there is no excess demand for licenses, the evolution of the eligibility ratio shows how the excess demand is reduced by increases in the prices of licenses over the course of an auction. 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 as a consequence of Eq. (1). 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. The PCS-C&F Block Reauction 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 com-

pared to the final prices. The analogous sum in these auctions was 0.084 and 0.104. Fig. 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.

3.2.2. Number of bidders

Fig. 2 graphs the number of bidders in the four 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 Fig. 1. As their eligibility drops towards zero, such bidders will be forced to leave the auction as illustrated in Fig. 2.

Reserve prices seem to have a strong influence on bidding activity early in the auction. In the PCS-C Block and
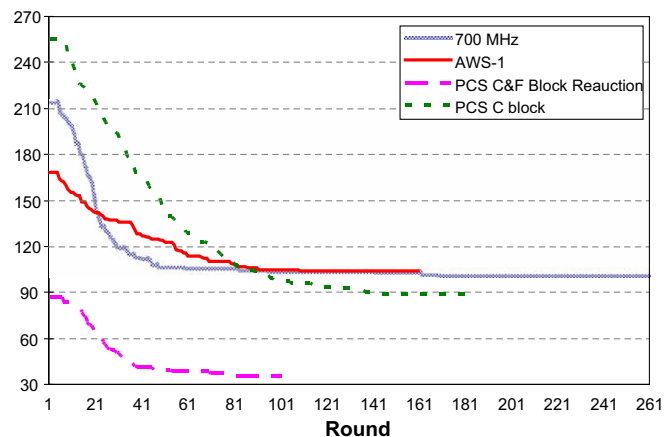

Fig. 2. Number of qualified bidders.

Table 6
Jump bids.

	PCS-C Block	C&F Block Reauction	AWS-1	700 MHz
All bids placed	27,865	19,798	16,197	36,418
Bids = MAB	14,236 (51.1%)	19,575 (98.9%)	15,957 (98.5%)	36,408 (99.97%)
Bids > MAB	13,527 (48.5%)	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	C&F Block Reauction	AWS-1	700 MHz
Total bids from round 2	27,763	18,893	15,466	34,569
Self-bumping bids	567 (2.04%)	43 (0.23%)	12 (0.08%)	265 (0.77%)

The FCC specified block-specific aggregate reserve prices in AWS-1 and 700 MHz. As the reserve prices were aggregate, it is not likely that many self-bumping bids were placed as an attempt to meet the reserve prices. One exception is Google's 9 self-bumping bids. (See Brusco et al. (2009)) The number of self-bumping bids made after the block-specific aggregate reserve prices were met is 10 in AWS-1 and 170 in 700 MHz.

the PCS-C&F Block Reauction 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 that 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.

4. 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.

4.1. Straightforward bidding

The concept of straightforward bidding is discussed in Milgrom (2000), Milgrom (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.[14] 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% of the Minimum Acceptable Bid (MAB). We define a self bumping bid as a case in which the provisionally winning bidder increases its 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% of the bids in the other three auctions. Also, 2% of the bids are self bumping in the C block compared to less than 1% in the other auctions. Recall that the 700 MHz had anonymous bidding and click box bidding. The AWS-1 auction and the PCS-C&F Block Reauction both had click box bidding. As we discussed in the introduction, click box bidding restricts the set of available bids and therefore

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[14] There are several empirical studies on the "non-substitutability" among licenses due to existence of synergy effects. See Ausubel et al. (1997), Moreton and Pablo (1998) and Bajari and Fox (2007).

possibly the scope to signal or intimidate other bidders in the auction. The PCS-C Block auction 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 opening bids. These or other factors could also be responsible for the part of the differences across Tables 6 and 7.

4.2. Additional tests of straightforward bidding

In this subsection, we describe another test of straightforward bidding. Let i denote a bidder 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 licenses 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 standing high bidder. If i is the current standing high 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 prices in round r for licenses on which i is active in round t.

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

$$v_i(S_{i,r}) - P_{i,r}(S_{i,r}) \geqslant v_i(S_{i,r'}) - P_{i,r}(S_{i,r'}), \qquad (2)$$
$$v_i(S_{i,r}) - P_{i,r'}(S_{i,r}) \leqslant v_i(S_{i,r'}) - P_{i,r'}(S_{i,r'}). \qquad (3)$$

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 in round r for $S_{i,r}$ that i faces. 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

$$P_{i,r}(S_{i,r}) - P_{i,r}(S_{i,r'}) \leqslant P_{i,r'}(S_{i,r}) - P_{i,r'}(S_{i,r'}). \qquad (4)$$

Note that the inequality (4) does not involve the valuations $v_i(S_{i,r})$ and $v_i(S_{i,r'})$ that 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

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 measures 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.

Fig. 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. The figure also shows evolution of bidding activities that enables one to compare $\phi(r)$ across the auctions with different levels of minimum opening bids and various lengths. 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 the PCS-C&F Block Reauction and the AWS-1 lie between these two extreme points. This is true, with a lesser extent, even if we only look at the rounds after the level of new activities dropped below 10% of the total MHz-pop sold. One obvious interpretation of these graphs is that relatively large minimum opening bids in AWS-1 and 700 MHz encouraged bidders to bid straightforwardly from earlier rounds than the C Block auction. Another interpretation 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 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.

4.3. 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.

$$\phi(r) = \frac{\sum\limits_{i \in I(r)} 1(P_{i,r}(S_{i,r}) - P_{i,r}(S_{i,r-1}) \leqslant P_{i,r-1}(S_{i,r}) - P_{i,r-1}(S_{i,r-1}))1(S_{i,r} \neq S_{i,r-1})}{\sum\limits_{i \in I(r)} 1(S_{i,r} \neq S_{i,r-1})}.$$
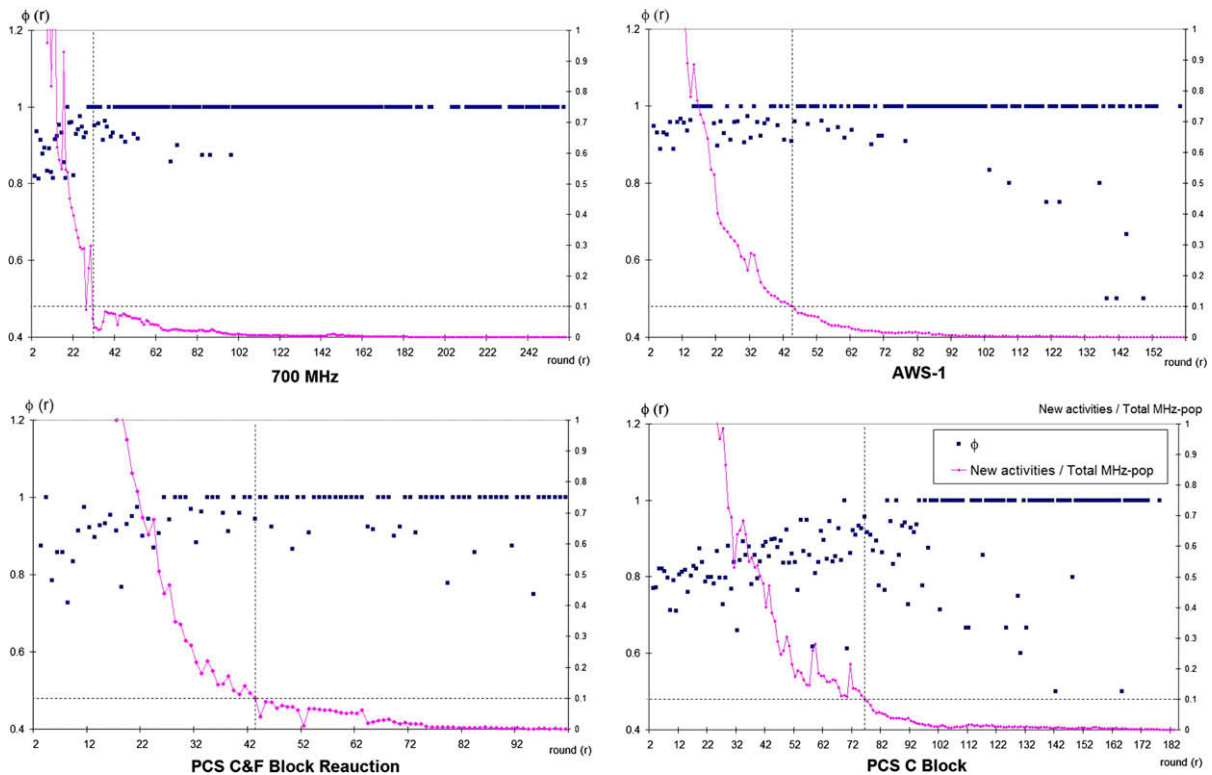
Fig. 3. Revealed preference with straightforward bidding.

For a bid made by bidder i on license l' in round r 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) The retaliating bidder i bids on license l within two rounds of placing the retaliatory bid.
(iii) 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.
(iv) 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 10 rounds.
(v) Bidder i's signal should be clear to j: there is only one j and one l' that meets (i) to (iv). 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 following criteria in order to be conservative in our definition of retaliation. In particular, we eliminate a bid returned by the above conditions if
(vi) The retaliating bidder did not consistently adhere to a punishment strategy: although j keeps bidding on l, i stops bidding on l'.

(vii) There is a round after round r in which i bid on l' although j did not bid on l.[15]

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 examine 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 its intentions to j by bidding on l'. Table 8 suggests that

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[15] The criteria we use are similar to ones in Cramton and Schwartz (2002). While they manually looked at bids that initially satisfy (i) and (ii) to check that they resemble code bidding or retaliating bidding in the PCS D, E, and F auction, the click box bidding used in AWS-1 and 700 MHz makes code bidding impossible. Instead, we develop an algorithm that imposes restrictions that they considered in their manual check procedure. For example, (iii) corresponds to 2, (iv) to 4, (v) to 3, (vi) to 1 and (v) corresponds to the third paragraph in page 6 of Cramton and Schwartz (2002). Rose (2007) performs a similar exercise which resulted in 31 bouts of retaliatory bids in the AWS-1 auction, but he does not provide the details of the restrictions used for his algorithm that allows for comparison of our results.

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

Conditions	AWS-1	700 MHz
(i)–(iv)	317 bouts	275 bouts
(i)–(v)	136 bouts	78 bouts
(i)–(vi)	103 bouts	67 bouts
(i)–(vii)	38 bouts	17 bouts

In total, 16,197 bids were made in AWS-1 and 36,418 in 700 MHz. As a result, the number of bouts of retaliation relative to the number of all bids is much lower in 700 MHz.

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.

5. 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 (forthcoming) 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 bidding, presence of large minimum opening bids and anonymous bidding that potentially make collusion more difficult. Click box bidding makes it harder for bidders to directly signal each other. Large minimum opening bids give bidders fewer rounds for communication via bids to work out a split of the licenses before prices become too high. 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, the PCS-C&F Block Reauction, 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, detecting collusion based solely on auction data can be difficult. However, we believe our results are suggestive that click box bidding, large reserve prices and anonymous bidding have limited the ability of firms to collude at FCC auctions.

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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