Collusive Bidding in the FCC Spectrum Auctions

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Abstract

This paper describes the signaling that occurred in many of the FCC spectrum auctions. The auction design, a simultaneous ascending auction, allowed bidders to bid on numerous communication licenses simultaneously, with bidding remaining open on all licenses until no bidder was willing to raise the bid on any license. Simultaneous open bidding allowed bidders to send messages to their rivals, telling them on which licenses to bid and which to avoid. This "code bidding" occurs when one bidder tags the last few digits of its bid with the market number of a related license. Such bids can help bidders coordinate a division of the licenses, and enforce the proposed division through targeted punishments. Often the meaning of a bid is clear without attaching a market number in the trailing digits. Such a "retaliating bid" need not end in a market number to warn off a rival from a contested market. We examine how extensively bidders signaled each other with retaliating bids and code bids in the DEF-block PCS spectrum auction held from August 1996 through January 1997. We find that only a small fraction of the bidders commonly used these signals. The price differences between those markets where signaling did and did not occur were negligible. However, bidders that used these collusive bidding strategies won more than 40% of the spectrum for sale and paid significantly less for their overall winnings, suggesting that the indirect losses from code bidding and retaliation may be large.

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1 Introduction

Beginning in 1994, the United States Federal Communications Commission (FCC) began auctioning spectrum licenses. A license allows the winning bidder to use a specified frequency band to provide wireless communication services to customers in a particular market. A collection of related licenses, typically all licenses in one or more bands, would be sold using a simultaneous ascending auction. The simultaneous ascending auction is a natural generalization of the English auction when selling many interdependent items.[1] Bidding occurs in rounds. In each round, bidders place *dollar* bids on any of the different licenses, raising the standing high bid by at least one bid increment. The auction continues until a round passes with no new bids, a round such that no bidder is willing to raise the bid on any license. The licenses then are awarded to the highest bidders, who pay the FCC the final bids.

During the DEF auction (the Personal Communications Services (PCS) auction for broadband frequency blocks D, E, and F) the FCC and the Department of Justice observed that some bidders used their bidding to coordinate the assignment of licenses. Specifically, some bidders engaged in *code bidding*. A code bid uses the *trailing digits* of the bid to tell other bidders on which licenses to bid or not bid. Since bids were often in the millions of dollars, yet were specified in dollars, bidders at negligible cost could use the last three digits—the trailing digits—to specify a market number. Oftentimes, a bidder (the sender) would use these code bids as retaliation against another bidder (the receiver) who was bidding on a license desired by the sender. The sender would raise the price on some market the receiver wanted, and use the trailing digits to tell the receiver on which license to cease bidding. Although the trailing digits are useful in making clear which market the receiver is to avoid, *retaliating bids* without the trailing digits can also send a clear message. The concern of the FCC is that this type of coordination may be collusive and may dampen revenues. The purpose of this paper is twofold: (1) to find the extent to which code bidding and retaliation occurred in the DEF auction, and (2) to estimate the revenue impact from this type of bid signaling.

The DEF auction is especially well suited for a study of collusive bidding strategies in a simultaneous ascending auction. The auction featured both small markets and light competition. Small markets enhanced the scope for splitting up the licenses. Light competition increased the possibility that

[1] See McMillan (1994), Cramton (1995, 1997), McAfee and McMillan (1996), and Milgrom (2000) for detailed descriptions of the simultaneous ascending auction.

collusive bidding strategies would be successful. Indeed, prices in the DEF auction were much lower than prices in the two early broadband PCS auctions.

We find that six of the 153 registered bidders in the DEF auction regularly signaled using code bids or retaliating bids. These bidders won 476 of the 1,479 licenses for sale in the auction, or about 40% of the available spectrum weighted by population covered. These signaling bidders paid about the same as other bidders for the F-block licenses, but on the D and E blocks, the signaling bidders paid \$2.50/pop, whereas nonsignaling bidders paid \$4.34/pop.[2] A possible explanation for this difference is that the bid signaling strategies were effective at keeping prices low on the D and E blocks where competition was not as stiff as on F licenses.[3] The auction is essentially a matching problem—assigning licenses to bidders—where the sequence of bids is used to determine the assignment. The auction ends when the bidders agree on the assignment. Those bidders using signaling may have been able to more quickly (at lower prices) coordinate the allocation of markets with its competitors.

Estimating the revenue loss caused by bid signaling is at best a difficult task. We begin with a standard econometric approach. Using the data on those markets where signaling was not used, we fit a reduced form regression that estimates license prices, based on a number of market attributes. We then use the fitted regression to predict prices in those markets where the winning bidder used signaling to warn off competitors. One measure of revenue loss is then the difference between the predicted price and the actual price in these markets. We find that the prices were not appreciably lower on the licenses won after successful bid signaling. Thus, one might conclude that the simultaneous ascending auction is remarkably immune to collusive bidding strategies. However, we believe that this is the wrong conclusion. There are two problems with trying to measure price differences on those licenses won with signaling. The first is selection bias. The markets where we observed bid signaling may be especially contested. Second, the threat of using signaling as a punishment against those bidders not adhering to some coordinated allocation of licenses could be used as leverage to lower prices on all licenses, not just those licenses where the threat was made good. Concluding that signaling has no effect in the auction would be like concluding that price wars are ineffective at keeping prices high for oligopolists. Indeed,

[2] Each license was for 10 MHz of bandwidth, but covered a different population. Since license value tends to be proportional to the population covered, it is common to compare licenses of equal bandwidth in terms of the bid per person covered, or \$/pop. Population is measured as of 1994.

[3] Though for each market, the D, E, and F licenses were near perfect substitutes, the F block license was set aside for small bidders with annual revenues less than \$125 million and with assets worth valued at less than \$500 million. These small bidders could bid on the D, E, and F blocks, but larger bidders could not bid on the F licenses. Additionally, small bidders received some combination of bidding credits and installment payments for F licenses, but not for D and E licenses, making the F licenses more attractive to them then the D and E blocks.

using a dummy variable approach, we find that those bidders who frequently used bid signaling achieved significantly lower prices on the D and E blocks than the other bidders.

The paper is organized as follows. In Section 2, we review the relevant literature on multiple-unit auctions and discuss how bidders' incentives may have induced them to use signaling to coordinate on a low-revenue equilibrium. We elaborate in Section 3 on the auction rules and how these rules enabled bidders to use signaling. In Section 4, we describe the technique we used to find evidence that bidders were signaling, and then summarize the code bidding and retaliation that occurred in the DEF auction. Section 5 contains our estimation of the revenue losses. We conclude in Section 6.

2 Demand Reduction and Collusion in Ascending Multiple-Unit Auctions

Bidders may wish to suppress their demands to keep prices low in a multiple-unit auction with uniform pricing (or, as in the case of the spectrum auctions, where prices can be arbitraged). The multiple-unit auction literature has recognized these incentives for sealed-bid uniform-price auctions; see for example Ausubel and Cramton (1996). These incentives may be more pronounced in an ascending version of the uniform-price auction, where bidding occurs dynamically and where there is information revealed about the bidding during the auction. To illustrate this, consider a simple example with two homogeneous goods and two risk-neutral bidders. Suppose that to each bidder the marginal value of winning one item is the same as the marginal value of winning a second item. These values are assumed independent and private, with each bidder drawing her marginal value from a uniform distribution on [0, 100]. First consider the sealed-bid uniform price auction where each bidder privately submits two bids and the highest two bids secure units at a per-unit charge equal to the third highest bid. Ausubel and Cramton's Example 8.4 (1996) shows that there are two equilibria to this sealed-bid auction: a demand-reducing equilibrium where each bidder submits one bid for $0 and one bid equal to her marginal value; and a sincere-bidding equilibrium where each bidder submits two bids equal to her marginal value. The sincere-bidding equilibrium is fully efficient in that both units will be awarded to the bidder who values them more. The demand-reducing equilibrium, however, raises zero revenue (the third highest bid is zero) and is inefficient since the bidder with the higher value wins only one unit.

Next consider the same setting, but where an ascending version of the auction is used. Specifically, view the ascending auction as a *two-button* auction where there is a price clock that starting from price 0 increases continuously to 100 while the bidders depress the buttons to indicate the quantity they are bidding for. Further, suppose that buttons are "non-repushable" meaning a bidder can decrease her demand but cannot increase her demand.[4] Each bidder observes the price and can observe how many buttons are being depressed by her opponent. The auction will end at the first price such that the total number of buttons depressed is less than or equal to two. This price is called the stop-out price. Each bidder will win the number of units she demands when the auction ends, and is charged the stop-out price for each unit she wins. Suppose that bidders *passively* form their beliefs: if at price P the auction has not ended, then each bidder believes that the other bidder's value is distributed uniformly on [P, 100]. A strategy will tell a player at what price to next change the number of buttons she depresses and to how many buttons, given any feasible history such that the auction has not ended.[5] Suppose weakly dominated strategies are eliminated, so that a player active on one unit will bid *sincerely*, meaning, she will continue to push the button at prices below her value and will depress zero buttons above her value. Suppose one bidder, say A, is active on one unit and the other bidder, say B, is active on two units, and the price $P < V_B$, where V_B is B's marginal value. Then, as shown in Ausubel and Cramton (1996, Example 8.3), any equilibrium in weakly undominated strategies calls for B to immediately reduce her bidding to one unit, since she prefers her payoff from winning one unit at the current price over her expected payoff of winning two units (which would require letting the price rise up to V_A). Next suppose at price P each bidder is active on two units. Each bidder knows that if she unilaterally decreases her bidding to one unit, the other bidder will instantaneously end the auction, as argued above. But since she prefers the payoff from winning one unit at the current price over the her expected payoff of winning two units at the price high enough to eliminate the other bidder from the auction, she will immediately bid for just one unit, inducing an *immediate* end to the auction.[6] Thus, the only equilibrium where bidders passively update their beliefs and where bidders eliminate weakly dominated strategies is analogous to the demand-reducing equilibrium in the sealed-bid uniform-price auction. The efficient equilibrium does not obtain. This example shows that the incentives to demand reduce can be more pronounced in an open auction, where bidders have the opportunity to respond to the elapsed bidding.

This example was meant to illustrate that in simple settings with few goods and few bidders, bidders have the incentive to demand reduce. Engelbrecht-Wiggans and Kahn (1999) and Brusco and Lopomo (1999) show that for an auction format like the FCC's, where the bidding occurs in rounds and bidding can be done on distinct units, that there exist equilibria where bidders coordinate a division of the available units at low prices (relative to own values). Bidders achieve these low-revenue equilibria by

[4] Bikhchandani and Riley (1991) give a thorough discussion of the different variations of button auctions for single-unit auctions, and artfully invent the word "non-repushable."

[5] Ausubel (1997) provides the precise specification of the histories and strategies for this game.

[6] Here *immediate* means at the same price. This can be done if the price clock stops whenever someone changes the number of buttons she depresses, as in Ausubel (1997).

threatening to punish those bidders who deviate from the cooperative division of the units. The idea in both the example and in these papers is that bidders have the incentives to split up the available units ending the auction at low prices. With heterogeneous goods and asymmetric bidders in terms of budgets, capacities, and current holdings of complementary goods, it is unlikely that bidders would be aware of a simple equilibrium strategy that indicates which licenses to bid on and which to avoid. Rather, we believe that bidders took advantage of signaling opportunities to coordinate how to assign the licenses. With signaling, bidders could indicate which licenses they most wanted and which licenses they would be willing to forgo. Often this communication took the form of punishments.

We view the type of coordination achieved with bid signaling as collusion. Specifically, we borrow the *working definition* given in Cramton and Schwartz (1999):

> *Collusion* occurs between two bidders if they have overlapping interests on several licenses and if these bidders agree to allocate these licenses such that each bidder wins a license for a price substantially (more than a bid increment) below what the other bidder is willing to pay. This working definition can be expanded to include more than two bidders.

It should be noted that this definition does not coincide with legal definitions of collusion or how economists have traditionally viewed collusion in auctions. For single-unit auctions, other work has modeled collusion with a ring of bidders that meets outside of the actual auction game to decide how to cooperatively bid in the auction (see, for instance, Graham and Marshall 1997, Mailath and Zemsky 1991).[7] The working definition of collusion does not require this extra stage game (the knockout auction), buts allows for collusive agreements to be negotiated through the bidding during the auction.

3 Auction Rules and Signaling Techniques

3.1 Auction Rules

In this section, we describe the rules for the DEF auction.[8] Each of 493 markets had three licenses for sale, one for the D, E, and F blocks. A license allowed the winner to that market (for example, Richmond, VA) access to a 10 MHz bandwidth of frequency suitable for PCS for a period of ten years and a chance at renewal after 10 years. In each round, each bidder could place bids on any of the licenses it was eligible to win (where eligibility was partially determined by the size of the bidder's down payment to the FCC). At the end of each round, the FCC reported the dollar amount of each bid on each license, along with which bidder placed the bid. If a license received new bids, then the highest bid became the

[7] Baldwin, Marshall, and Richard (1997) provide a brief review of the theoretical and empirical work on collusion in auctions. See also Marshall and Meurer (1999) for a legal perspective; this paper also overviews much of the economic literature on collusion.

[8] The rules were generally the same, but evolved somewhat from auction to auction. For a summary of the rule changes see Cramton and Schwartz (1999).

standing high bid, and the corresponding bidder became the standing high bidder. Bids are made in whole dollars and must be above the minimum bid determined by the FCC. The FCC posted the minimum bids for the next round at the conclusion of each round. The minimum bid typically was 5%, 10%, or 15% higher than the standing high bid, and after round 126, the bid increment was held constant at 10%. The auction would not end until a round passed in which no new bids are placed. The standing high bidders win the corresponding licenses at a gross price of their standing high bid. Some bidders had bidding preferences, however, that reduced the amount they paid the FCC if they won licenses in the F-block, which were set aside for preferenced bidders (larger bidders like AT&T could not bid on the F-block licenses, though smaller, preferenced bidders could bid on the D and E-block licenses).[9]

For more on the auction rules that we have not discussed, such as activity rules and withdrawal rules, see Cramton (1995, 1997); for the precise rules of the DEF auction, see the Bidder Information Package located on the FCC's web site (at http://www.fcc.gov/wtb/auctions).

3.2 Signaling Techniques

Code bidding occurs when one bidder encodes a meaningful market number in the trailing digits of her bid. A bidder can signal a rival by bidding on a license that the rival is the standing high bidder on, while attaching in the three-digit number of the market it wants the rival to stop bidding on. This signal can impose a cost on the rival. If the rival wants to win the license it was bumped from, it will have to place a higher bid on the license (bids must be raised by at least a bid increment, typically 10%). An example of this is signaling technique is shown below.

Table 1: Example of Code Bidding

	Marshalltown, IA 283 E		**Rochester, MN 378 D**		Waterloo, IA 452 E		
Round	McLeod	USWest	McLeod	**USWest**	AT&T	McLeod	USWest
24	56,000					287,000	
…			…	…			
46				568,000			

[9] If a bidder had annual average income of less than $40 million over the last three years, it received a credit on the price it paid for the F-block licenses it won, the credit being either 15% or 25% depending on how small its annual average was. Additionally, bidders with less than $75 million could receive special financing from the FCC on those F-block licenses it won; some were eligible for eight to ten year loans at the ten-year US Treasury obligation rate depending on their annual average income. For precise, specifications, see the DEF Bidder Information Package located on the FCC's web site at http://www.fcc.gov/wtb/auctions. When calculating losses and gains subsequently in this paper, we discount the F-block gross bids according to the precise preferences of the winning bidders; a good rule of thumb is that the bidding credit and the special financing arrangement are worth about a 50% bidding credit, meaning a preferenced bidder is indifferent between winning the F-block of Richmond, VA for a gross bid of $2 million and winning the D or E block of Richmond with a bid of $1 million.

52			689,000				
55				723,000			
58			795,000				
59				875,000			**313,378**
60						345,000	
62			963,000				
64		**62,378**		1,059,000			
65	69,000						
68					371,000		

Table 1 shows all of the bids that were made on Marshalltown, block E and Waterloo, block E after round 24, and all of the bids on Rochester, block D after round 46. USWest and McLeod were contesting Rochester, trading bids in rounds 52, 55, 58, and 59. Rather than continue to contest Rochester, raising the price for the eventual winner, USWest bumped McLeod from Waterloo in round 59 with a code bid, $313,378. The “378” signified market 378—Rochester. USWest’s bid revealed that McLeod was being punished on Waterloo for bidding on Rochester. In round 60, McLeod retook Waterloo, bidding $345,000, $58,000 more than its round 24 bid. But McLeod did not yet concede Rochester—it placed another bid on Rochester in round 62. USWest then used the same technique in round 64, punishing Marshalltown instead. USWest’s bid in round 64 on Rochester won the license. (We have shown only two of the markets that USWest punished McLeod on for expositional ease; USWest had actually punished McLeod on several markets contemporaneously.)

There are several variations of this type of code bidding. For example, after bumping a rival with a code bid, a bidder can then withdraw its bid. In this case, the rival can regain the license it was bumped from by placing its prior bid. This does not raise the price for the rival, but can be effective in getting the rival’s attention. Sometimes, a bidder will code bid on the market it wants the rival to stop bidding on; in this case, the market number contains the market number that will be punished should the rival not cease its bidding on the market the code bidder wants. When this type of code bid is used in tandem with a punishing code bid, this is known as *reflexive code bidding*.

Though in the above example of code bidding, USWest effectively uses “378” in its bids to signal its intent, retaliation in no way requires the “378.” So long as it is clear which market the signaling bidder wants its rival to cease bidding on, the same sorts of punishments can be made without the trailing digits. When a punishment is made without the trailing digits we call this a *retaliating bid*.

Table 2: Example of Retaliation

	Canton, OH 65 F			Harrisburg, PA 181 F	
Round	NextWave	**NorthCoast**	OPCSE	NextWave	NorthCoast
56			358,000	1,217,000	
57		409,011			
78	460,000				
82		511,011			
125			562,000		
136		618,011			
158	680,000				
159		748,011			
160	861,000				
161					**1,339,011**
162				1,473,000	
163		947,011			

Table 2 shows how retaliation works. It shows all of the bids that were made on block F of Canton and Harrisburg after round 56. NextWave and NorthCoast were contesting Canton, trading bids in rounds 158, 159, and 160. Rather than continue to fight it out on Canton, raising the price for the eventual winner, NorthCoast retaliates. The retaliation was the bid of $1,339,011 on Harrisburg in round 161, which bumped NextWave on a market it held since round 56. (Note that the "011" that NorthCoast ends it bid with is not in itself a coded signal; NorthCoast ended many of its bids with "011" as its signature, similar to GTE ending its bids in prior auctions with GTE's telephone numeric representation "378")

Other types of signaling include jump bidding, double bidding, and raising one's own bids. The interested reader is referred to Cramton (1997), but we do not treat these here: these strategies involve punishing oneself to intimidate others and it is unclear what agreement this suggests. A bilateral signaling technique that we do not discuss in this paper is that of strategic withdrawals, where a bidder withdraws from a license that a rival desires as an inducement to get the rival to stop competing on another market (see Cramton and Schwartz, 1999, who discuss the few occurrences of this in the DEF auction).

4 Code Bidding and Retaliation

4.1 Detection Methodology

To find the retaliating bids and code bids in the DEF auction, we needed a consistent way to comb through the 23,157 bids, looking for those bids resembling those examples in Section 3. Our strategy was to loop through each bid, to tentatively assume the bid was a retaliating bid, and then to check whether the bid met criteria characteristic of retaliating bids. For each bid, we used the reported information to determine which bidder made the bid, which bidder it bumped when it placed the bid (i.e., the standing high bidder as of the prior round), the market and block, and the round the bid was placed. For a bid to be a retaliating bid, it must be clear to the bidder being bumped that the bid was not meant to win the license, but was only meant to punish. Therefore, we first eliminated all bids made by a bidder who had shown interest by bidding on any block of the same market in the prior ten rounds. Of course, if a retaliating bid was made in the previous 10 rounds, and then a follow-up retaliating bid was made, our algorithm did not catch the second retaliating bid—the program was designed to only catch the first retaliating bid.

To be a retaliating bid, we required a clear motive: the bumped bidder must have recently been bidding for a market the retaliating bidder wanted. To ensure this, we required that the bumped bidder bumped the retaliating bidder from some license in the prior two rounds. We also required that within two rounds of placing the retaliating bid, the retaliating bidder had bid on the contested market; otherwise, it is unclear what the retaliating bid was meant to accomplish.

If a bid passed all of the above obstacles, then it certainly met many characteristics of a retaliating bid. Our next step was to examine all of the bids returned from the above algorithm to further check that they resemble code bidding or retaliating bidding. Sometimes by looking at the retaliating bid we learned that the bid was not intended as retaliation. For example, if the bidder had bid on this market intermittently throughout the auction, then the bid was probably not meant as punishment. This part of our checking process was subjective. Other subjective criteria that we used to eliminate the results returned by our algorithm included:

1. The bidder did not consistently adhere to a punishment strategy. If it punished once and it was not successful in deterring its rival, and then no follow-up punishing bids were placed, then we did not view this as a retaliating bid.[10]

2. The retaliating bid worked too quickly. If only one retaliating bid was placed and on a market the retaliating bidder had shown interest on earlier in the auction, if the retaliating bid did not contain a relevant market number, and if the competitor conceded, then we view this as coincidental, and not strong enough evidence to conclude that this was a retaliating bid.[11]

3. The intentions of the bidder were unclear. If the bidder and the punished bidder were competing contemporaneously on several markets, and the punishing bid did not contain a market number, then we view these bids as being ambiguous in intent.

[10] It could be that we miss some retaliating bids this way, but these are not serious misses, since the signaling had not worked. Because of omitting these cases however, we may be underestimating punishments.

[11] This may be the most serious omission in our technique, we are omitting those cases that worked the fastest. However, our goal is to only include those cases where the evidence is obvious enough that signaling occurred.

4. The punished bidder did not securely hold the high bid on the license being punished. If a third bidder was bidding on this market in the three rounds prior to the punishing bid, then it is not clear that punishment had any bite.

It is probably impossible to list all of the subjective factors we used to determine whether a bid returned by our algorithm was indeed a retaliating bid; however, the above factors were the most important. Because our program returned 1,397 retaliating bids in rounds 10 to 40, we only considered retaliating bids (that did not include trailing digits) which occurred after round 40. This omission was probably innocuous since in this 275 round auction, few markets were settled by round 40 if two bidders actually were actively contesting these markets. From round 40 and up, our program returned 559 bids for us to check. Whenever the examined bids ended in the market numbers of the markets involved, we categorized this as a code bid.

4.2 Evidence of Signaling

Using the techniques described in Section 4.1, we have combed through the 23,157 bids looking for retaliating bids and code bids. Our program returned 559 incidences of candidate retaliating bids for us to check by looking at the bidders and markets involved. On checking these, we have confirmed 37 separate bouts of retaliation and code bidding, where a bout can involve several rounds of retaliation over several markets.

Table 3: Bouts of Retaliation in the BTA DEF Auction

	With Code Bids		Without Code Bids		
Blocks	D or E	F	D or E	F	Total
Successful	5	7	3	4	19
Unsuccessful	3	8	4	3	18
Total	8	15	7	7	37

Table 3 classifies the retaliation bouts by which blocks they occurred in, by whether code bids where used (as opposed to retaliating bids without trailing digits), and whether or not the signals were successful. Our definition of successful is quite strict: the signaling bidder must have placed the winning bid on the license it sought within five rounds of placing its retaliating bid(s). Unsuccessful is simply the negative of successful—it includes cases where the signaling bidder was unable to dissuade its rival from the license it desired and cases where another bidder later bids on the license. Bidders used code bidding to try to win licenses 23 (= 8 + 15) times, 12 times successfully. Retaliations that did not include code bids occurred 14 times, 7 times successfully. We have found more cases of code bidding, but we note that code bids were easier to find, and also we looked for code bids that occurred all through the auction, not just after round 40.[12, 13]

Table 4: The Main Retaliating Bidders

	Bouts Initiated		
	With Code Bids	Without Code Bids	Total
21Century	3	0	3
AT&T	1	3	4
Mercury	7	1	8
NorthCoast	0	5	5
OPCSE	7	1	8
USWest	3	1	4

Table 4 shows all of those bidders who initiated more than one bout of retaliation or code bidding. The table shows that these bidders mostly used one technique or the other. AT&T used code bidding early in the auction (round 20) expelling Powertel from Birmingham, AL, but for whatever reason decided not to use trailing digits in its retaliating bids thereafter. It is likely that a bidder like AT&T knew it had much to lose if it attracted the FCC's attention by code bidding. Another interesting point to note is that 75 licenses were punished with code bids and retaliating bids. Over 90 bids ending in market numbers were part of code bids.

5 Revenue Effects from Code Bidding and Retaliation

5.1 Direct Methods

Given a sample of single-unit auctions where there is data on which auctions bidding rings participated, two ways to econometrically estimate the revenue losses from collusion are: (1) a dummy variable approach; and (2) a forecasting approach. In the dummy variable approach, each auctions' revenues are regressed against explanatory variables and a dummy variable which indicates the presence of a bidding ring. The coefficient on the dummy variable indicates the magnitude of the revenue losses from collusion. In the forecasting approach, for the sample of auctions where collusion has not occurred, a regression of revenues against the explanatory variables is fitted. This estimated relationship is then used to predict auction revenues for those auctions where collusion has occurred. The difference between

[12] Finding code bids was easier since we could narrow our search to just bids ending in market numbers (1-493). There were 1,551 bids ending in 1 which we ignored, since it is unlikely these bids had anything to do with market 001 (Aberdeen, SD), but more likely that these bids were simply a trick to top (by a $1) an opponent bidding in the same round.

[13] See Appendix I for a more detailed listing of the retaliating bids. The FCC's web site, http://www.fcc.gov/wtb/auctions, contains links to the bidding data for the DEF auction as well as other spectrum auctions.

actual revenues and predicted revenues then gives is taken as an estimate of the losses for an auction where collusion has occurred. There are two advantages of the forecasting approach: (1) it gives a specific number for an individual auction, rather than a collective result; and (2) it does not constrain the structural parameters to be identical across the collusion and noncollusion samples. Howard and Kaserman (1989) discuss more fully each approach in the context of single unit auctions, citing many court cases. We adapt these approaches to the multiple-unit but single auction setting that we have with the DEF auction.

5.1.1 Dummy Variable Approach

For the dummy variable approach, we use a regression that predicts the prices of the licenses, using as one explanatory variable a dummy variable that indicates whether signaling was used successfully to dispel a competitor.[14] Ausubel et al. (1997) estimate a parsimonious benchmark model to predict prices in the AB and C auctions. We borrowed their model, making only slight modifications. The idea is to do two regressions, one to estimate the net price for F-block licenses and one to estimate the average of the D and E-block prices.[15] We take as the net price, the net bid divided by the 1994 population (net bid = gross bid for the D and E blocks). Our dependent variables will be the natural logarithm of the net price ($/pop) in the F-block and the log of the average price of the D and E blocks ($/pop). Our independent regressors, informed by Ausubel et al. (1997) include the log of population density, microwave links per million of people in 1994, the log of 1994 population, the fraction of households with income more than $35k, and a competition variable.[16, 17] The competition variable we use differs from that in Ausubel et al. They are able to exploit the restrictions in those auctions on who can win which licenses based on the then current cellular holdings to compute a competition variable. However, since in the DEF auction there were much fewer restrictions stating which bidders can bid on which licenses, we formed a new competition variable. For the F-block we take as our competition variable the cumulative number of

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[14] Our definition of success was defined in the previous section as those markets where a bidder used retaliating bids (or code bids) to drive off a competitor from a contested market, and within five rounds of placing the retaliating bid, the bidder places the winning bid on the (formerly) contested market.

[15] We note that the F-block was set aside for preferenced bidders, small (measured by annual income or assets) bidders who received bidding credits and financing arrangements on those F-block licenses they won (further details are in section 1. Unpreferenced bidders were not eligible to bid on F-block licenses; however, preferenced bidders could bid on D and E-block licenses. Because of these arrangements, an F-block license was not a close substitute with its D and E counterparts. Since the D and E-blocks were near perfect substitutes, we averaged their winning bids.

[16] We note that Moreton and Spiller (1998) estimate a similar model as Ausubel et al. (1997), but use for the dependent variable the natural logarithm of the bid rather than the natural logarithm of price, which divides the bid by population. Given that in both specifications, the natural logarithm of population is used as a regressor, both specifications give the same estimated coeeficients and standard errors for all of the other regressors. Since population is the main determinant of the bid, the explained variation is much higher using log bid as the independent variable rather than log price.

[17] This specification assumes a constant elasticity between bid and population, other factors held constant.

bidders who place a serious bid (more than $500) in the first five rounds of the auction. For the D and E-blocks, we take the cumulative number of bidders placing a serious bid on either block in the first five rounds. Since an auction with 153 registered bidders and 1,479 licenses is likely to take several rounds to settle (the earlier AB and C block auctions each lasted more than 100 rounds), the decision of a bidder to bid in the first five rounds is exogenous, not influenced by the final price in the market. We also take the C block price ($/pop) and the AB ($/pop) as regressors since these variables may help explain the variability in the DEF auction prices. Given the competitiveness in the C-block auction, these prices should be expected to fairly reflect the relative value differences between the different Basic Trading Areas (BTAs). The AB auction prices are more crude since in this auction the country was split into 51 Major Trading Areas (MTAs) rather than 493 BTAs. The other variables we use are explained in the next few paragraphs when interpreting the results. Summary statistics for the data are given in Table 5.

Table 5: Summary Statistics

Variable	Mean	Std. Dev.	Min	Max
Log of DE price ($/person)	0.420	1.122	-3.740	3.858
Log of net F price ($/person)	-0.319	1.176	-4.711	2.111
Log of net C price ($/person)	2.233	0.730	-0.280	3.687
Log of AB price ($/person)	2.417	0.625	-0.368	3.414
Cumulative number of bidders on D, E blocks in first 5 rounds	2.402	1.203	0.000	7.000
Cumulative number of bidders on F blocks in first 5 rounds	0.696	0.763	0.000	4.000
Log of population density of buildout area	5.349	1.459	0.465	8.779
Ten-year population growth, 1990-1999	0.098	0.089	-0.190	0.494
Microwave links per hundred million people	0.149	0.230	0.000	1.909
Log of 1994 population	12.383	1.086	10.203	16.721
Fraction of households with annual income > $35k	0.466	0.092	0.095	0.753

Notes: Sample size is 493.

Using ordinary least squares we regressed separate regressions for the DE prices and the F prices using the above regressors along with two dummy variables representing whether a market was punished or whether signaling was used successfully to win the license. Results are listed in column (1) of Table 6 and Table 7. The fit of these regressions is adequate, though not spectacular. However, heteroskedasticity loomed. Sorting the data by population from small markets to larger markets, and then performing a Goldfeld-Quandt test for heteroskedasticity (where the null hypothesis is homoskedastic errors) leads to rejecting the null, and accepting the unfortunate result that the errors were heteroskedastic. This technique shows the regression fits the data better for the more highly populated markets. This feature might make sense if bidders are more likely to form more careful value estimates for larger markets than for smaller markets. To counter this heteroskedasticity, we run the same regression but weight the data by 1994 population (the results listed in column 2 of Table 6). Even so, this weighting does not eliminate the problem, and from the large Goldfeld-Quandt test statistic it still looks we are not placing enough weight on the larger markets. However, we stick with weighting the data by the population for the remainder of the paper, since we believe that counting markets with large populations more heavily leads to a cleaner interpretation of the data. Because of the potential heteroskedasticity we report t-statistics calculated using robust standard errors.[18]

The OLS regressions for the DE and F prices with robust standard errors are reported in column (2) of Table 6 and Table 7. Our competition variable (the cumulative number of bidders in the first five rounds) does very well, having a positive slope that is significant at conventional levels. Also as expected the C-block is a strong regressor, having a positive coefficient that is significant at conventional levels. The coefficient on the AB price shows up insignificant in both the DE and F regressions. The slope of the population growth variable is significant in both regressions. The slope on the population density variable is significant in the DE price regression, but insignificant (at the 5% level) in the F price regression. The microwave links per 100 million people is of the wrong sign in both regressions. This variable measures the number of microwave links in the C-block, a proxy for the number in the D, E, and F blocks, and can be viewed as encumbrances on the license. The winning bidder on a block with a microwave link is responsible for the costs of relocating it. Therefore, prices on these license should be lower since the winner must bear the cost of microwave link removal. Since the dependent variable is in per capita terms, we had no expectation on whether the population variable would positively or negatively affect price (the elasticity of the bid with respect to population is equal to one plus the coefficient on the population variable). Of the wrong sign is the coefficient on the income variable, the fraction of households earning more than $35 thousand per year. The coefficient implies a negative relationship between this variable and prices. One might presume that this means that low income families consume more PCS than higher income families (this is possible), but a better story is that the fraction of households earning more than 35k is capitalized in the C prices, which is positively related with the DE and F prices. On all of the demographic regressors the interpretation should be how the variable affects the dependent variable aside

[18] A basic treatment of heteroskedasticity, the Goldfeld-Quandt test, and White's (1980) correction of standard errors are given in Greene (1993).

from its indirect effect through C prices. Or, to put it econometrically, our parameter estimates are reduced form estimates, not structural parameter estimates.

In the column 1 and 2 regressions we also used a dummy variable to click off those markets where signaling was used successfully and a dummy to click off those markets that were punished. The punish dummy variable's coefficient is positive and significant at the 5% level in both the DE and F regressions for the unweighted regression (column 1) but not for the weighted regression (column 2). One interpretation here is that punishments occurred more on smaller markets than on larger markets. The coefficient on the signaling dummy variable was insignificant in both the DE and F regressions, and in both the weighted and unweighted regressions. This lack of significance is a quite intuitive result. There is a selection problem in that it is the markets that are being contested that entice the retaliating bidders to use punishment to ward off rivals. In many cases (see the example in Table 1), successful retaliation took several rounds, while the price continued to rise on the contested market.

5.1.2 The Forecasting Approach

Rather than estimate the revenue losses with dummy variables, which act to average the effects of signaling that worked quickly with long, drawn out signaling that was eventually successful, we reestimate the model omitting those licenses where signaling occurred. These regressions are listed in column (3) of Table 6 and Table 7. Using the estimated regression, we predict what price should have been in those markets won after retaliating against competitors, and then by exponentiating and multiplying by population, we predict net bids. We take as the loss the predicted price less the actual price. These results are listed in the column labeled 3 in Table 8.

Because the DE and F prices were determined in the same auction, it makes sense that their prices are simultaneously determined—the F prices affected the D and E prices and vice versa. This is especially true since many preferenced bidders had bid on D and E licenses during the auction, and in fact, preferenced bidders won 147 D and E-block licenses. To this end we also performed our analysis using as regressors the log of the F-price in the DE regression and the log of the DE price in the F regression. Since these variables are endogenous, we used the competition variable as instruments in a two-stage least squares approach. These regressions are listed in column 4 of Table 6 and Table 7. Using these regressions to predict prices and losses yields the results given in the column marked 4 in Table 8.

Table 6: Price Regressions for D and E Blocks

	Log of DE Price ($/pop)			
	OLS	OLS	OLS	2SLS
Variable	(1)	(2)	(3)	(4)
Log of net C price ($/pop)	0.340	0.441	0.461	0.070
	(3.99)	(4.58)	(4.65)	(0.16)
Log of AB price ($/pop)	-0.032	0.016	0.017	0.060
	(0.44)	(0.19)	(0.20)	(0.58)
Cumulative number of bidders on D, E blocks in first 5 rounds	0.369	0.290	0.288	0.183
	(10.11)	(7.74)	(7.66)	(1.64)
Log of population density	0.098	0.121	0.104	0.060
	(2.33)	(2.24)	(1.88)	(0.88)
Ten-year population growth, 1990-1999	1.513	1.854	1.852	1.987
	(2.95)	(4.03)	(3.75)	(3.01)
Microwave links per hundred million people	0.498	0.942	0.865	0.691
	(2.42)	(3.53)	(3.23)	(2.19)
Log of 1994 population	0.074	0.114	0.102	0.188
	(1.31)	(2.48)	(2.05)	(1.70)
Fraction of households with annual income > $35k	-1.489	-3.272	-2.822	-2.440
	(2.75)	(6.15)	(3.55)	(3.00)
Punish Dummy = 1 if D or E block punished	0.396	0.180		
	(2.43)	(0.98)		
Signal Dummy =1 if a bidder won D or E block with retaliation	0.037	-0.197		
	(0.11)	(0.82)		
Constant	-2.146	-2.173	-2.169	-2.028
	(3.68)	(5.91)	(5.80)	(2.89)
Predicted value of the log of F-block net price ($/pop)				0.344
				(0.90)
Markets included where retaliation was used to win any block	yes	yes	no	no
Sample Size	493	493	473	473
R^2	0.325	0.449	0.429	0.560
Goldfeld-Quandt F-Statistic	1.344	2.426	2.525	1.928
numerator degrees of freedom	153	153	154	153
denominator degrees of freedom	153	153	144	143
p-value of Goldfeld-Quandt	0.034	0.000	0.000	0.000

Notes: Absolute values of t-statistics in parentheses, column (1) uses the OLS standard errors, all other standard errors are robust (White corrected), in regressions (2)-(4) the data is weighted by 1994 population.

Table 7: Price Regressions for F Block

	Log of F Price ($/pop)			
	OLS	OLS	OLS	2SLS
Variable	(1)	(2)	(3)	(4)
Log of net C price ($/pop)	0.658	1.298	1.341	0.666
	(7.18)	(4.14)	(4.24)	(3.06)
Log of AB price ($/pop)	-0.104	-0.056	-0.051	-0.150
	(1.32)	(0.36)	(0.31)	(0.90)
Cumulative number of bidders on F block in first 5 rounds	0.297	0.286	0.301	0.107
	(4.69)	(2.53)	(2.57)	(1.01)
Log of population density of buildout area	0.085	-0.005	-0.025	0.013
	(1.91)	(0.06)	(0.27)	(0.19)
Ten-year population growth, 1990-1999	1.680	0.158	0.165	-2.064
	(3.04)	(0.12)	(0.12)	(1.30)
Microwave links per hundred million people	0.619	0.569	0.475	-0.371
	(2.80)	(1.38)	(1.18)	(0.84)
Log of 1994 population	-0.087	-0.267	-0.254	-0.365
	(1.43)	(1.57)	(1.47)	(2.31)
Fraction of households with annual income > $35k	-0.348	-1.138	-1.399	1.662
	(0.59)	(1.85)	(1.71)	(1.54)
Punish Dummy = 1 if F block punished	0.379	-0.156		
	(2.07)	(0.50)		
Signal Dummy =1 if a bidder won F block with retaliation	0.408	-0.074		
	(1.36)	(0.27)		
Constant	-1.246	0.539	0.469	1.998
	(1.94)	(0.27)	(0.24)	(1.09)
Predicted value of the log of DE-block price ($/pop)				0.996
				(4.08)
Markets included where retaliation was used to win any block	yes	yes	no	no
Sample Size	493	493	473	473
R^2	0.272	0.295	0.301	0.467
Goldfeld-Quandt F-Statistic	1.542	1.621	1.749	1.150
numerator degrees of freedom	154	154	154	153
denominator degrees of freedom	153	153	144	143
p-value of Goldfeld-Quandt	0.004	0.001	0.000	0.199

Notes: Absolute values of t-statistics in parentheses, column (1) uses the OLS standard errors, all other standard errors are robust (White corrected), in regressions (2)-(4) the data is weighted by 1994 population.

Table 8: Estimated Losses

	Regressions		Bid Increments			
	(3) OLS	(4) 2SLS	1	2	4	6
DE Code Bidding	-1.2	-1.1	0.3	0.7	1.6	2.7
DE Retaliation	2.7	3.6	0.9	1.9	4.2	6.9
F Code Bidding	1.6	2.9	0.6	1.2	2.7	4.4
F Retaliation	-1.5	0.5	1.2	2.5	5.6	9.3
Total Losses $M	1.5	5.9	3.0	6.3	14.0	23.3

The losses in columns (3) and (4) of Table 8 are calculated by summing the difference between the predicted price and actual price for each license won following a successful bout of retaliation. Some of the losses on particular licenses are positive (meaning that the predicted price exceeded the actual price) and some are negative. In total, columns (3) and (4) show that predicted losses were $1.5 and $5.9 million respectively, which is small relative to the total net auction revenues of over $2 billion. Even summing only those losses that are positive yields estimated losses $5.3 and $9.4 using the OLS and 2SLS regressions, with most of the losses attributable to block D of Seattle, WA and block F of San Juan, PR. Given the technique we have used to estimate direct losses on these markets, building confidence intervals around the estimated losses would be difficult and would be problematic given the heteroskedasticity inherent in our regressions. As a rough check, the losses on the markets that were successfully won by fending off rivals with retaliating bids were not two standard deviations more than the mean of the in-sample losses. And regardless of confidence intervals, the losses estimated here are very small in magnitude.[19]

5.1.3 Ad Hoc Approach

Another sensible approach to estimate the direct losses is to simply assume that the bids would have risen another, say, two bid increments. (Prior to round 129, the minimum bids are 10 percent of the previous high bid when in the previous two rounds there were between 1 or 2 bids on the same license in the F-block or 1 or 2 bids on the D and E blocks combined. During the auction, the FCC decided to simplify the bid increment rule so that beginning in round 127, the bid increment was 10% regardless of the prior bidding activity.) The total net bids on those licenses successfully won via signaling was $30 million. Therefore if we assume the bid would have gone up by another X minimum bids before the final

[19] One must still interpret these results with caution. Because the prices were estimated in logs, and because the predicted prices are taken by exponentiating the predicted value of the log prices, Jensen's Inequality means that our predicted prices are underestimated so that the predicted losses are underestimated. To avoid this problem, one could take as a dependent variable prices rather than log prices; however, this yields a more poorly fitted model. With price as a dependent variable, the estimated losses are around $18m using OLS, and around $36 million using two-stage least squares. Still, it is Seattle and San Juan responsible for most of the losses.

price were reached, we can take as an estimate of the losses $\$30 \cdot 1.10^X - \$30$. For various values of X, this estimate of loss is shown in Table 8.[20]

5.2 Punishments Raised Prices

Punishments raised the prices on those markets where it occurred. The coefficients on the dummy variables are significant under all specifications. In fact, when a bidder is looking for a market to punish, markets not being actively competed on and with low prices are the best. It is these markets that the punishments have the most bite. Without the retaliations it is likely that many of the punished markets would have been sold for a very low price. We manually construct the gains from retaliation. Our process here is simple. The idea is to take the gain as the final price less the price the punished bidder would have won the license had the license not been retaliated on. For example, suppose bidder A held New Orleans for $100K, and bidder B then punished bidder A with a bid of $110K. Suppose bidder A then recaptures this market with a bid of $121K, and this turns out to be the winning bid. Then we would take the gains from retaliation to be $21K, the difference between what A paid less what it would have paid had the retaliating bid never occurred. If following the retaliation, another bidder (not A or B) bids on this market, then we assume that the retaliator did not affect the price on this market, unless of course B continues to punish this market after A retakes the license. This technique yields estimated gains of $5.5 million. Netting out the gains and losses yields net losses of less than $17.8 million even if we take the 6-bid increment estimate of losses. On an auction netting over $2 billion dollars this is not alarmingly high.

5.3 Indirect Methods

5.3.1 Price Differences Between Signaling Bidders and Nonsignaling Bidders

The direct estimates of the revenue losses attributable to signaling are small. But as alluded to earlier, these direct methods are flawed because of a selection problem. A bidder need only use such a drastic device as signaling if a competitor is actively driving up the price. Additionally, section 3.2 shows that we usually require much evidence to identify retaliating bids, this identification being more clear-cut when there are several rounds of bidding on the contested and punished markets. In fact, if we view punishments as occurring only when cooperative agreements break down, then we should expect the prices to be lower on those markets where signaling was unnecessary. On markets where prices are low,

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[20] It may be reasonable to assume that bidding would have risen by another 6 increments. For example, in the case of Mercury punishing High Plains to force High Plains off of Lubbock, TX block F, High Plains eventually won the E block price for $2.38 million. High Plains did not receive a bidding credit or financing arrangement for this block, meaning roughly that High Plains would have been willing to bid up to twice this amount on the F-block license. So if we assume that the price on Lubbock, block F, could have risen to $4.76 million from the actual gross bid of $2.33 million, then this translates to the price rising by about 7.5 bid increments. Of course this assumes that Mercury would have continued to bid on Lubbock block F.

the mere threat of retaliation may be enough to achieve cooperation, bidders knowing that if they can achieve consensus on who wins which licenses, that bidders will punish deviant behavior (see McAfee and McMillan, 1997, page 170). A natural question to ask is whether the bidders who actively use punishments can achieve favorable prices relative to bidders who do not use signaling.

We find that six of the 153 registered bidders in the DEF auction regularly used signaling devices in the auction. These bidders won 476 of the 1,479 licenses for sale in the auction, or about 40% of the available spectrum measured by 1994 population (each license was 10MHz but covered a different region with a different population). Table 9 shows that those bidders who used signaling as a part of their strategy achieved much lower prices on the D and E blocks relative to those bidders who did not signal. Yet, on the F block, where there was more competition, average prices are nearly the same for the signaling and nonsignaling bidders.

Table 9: Average Prices Paid ($/pop)

	Blocks	
	D and E	F
Signaling Bidders	**2.52**	**1.67**
AT&T	2.77	—
21Century, Mercury,	2.07	1.67
Nonsignaling Bidders	**4.34**	**1.65**
Sprint	6.16	—
Excluding Sprint	3.58	1.65

Table 10: DE-Block Regressions That Show Signaling Bidders Paid Less

	Log of DE Price ($/pop)			
	OLS	2SLS	OLS	2SLS
Variable	(1)	(2)	(3)	(4)
Log of net C price ($/pop)	0.461 (5.06)	0.342 (1.02)	0.457 (5.05)	0.212 (0.68)
Log of AB price ($/pop)	0.048 (0.56)	0.059 (0.69)	0.030 (0.35)	0.052 (0.60)
Cumulative number of bidders on D, E blocks in first 5 rounds	0.232 (6.29)	0.203 (2.23)	0.217 (5.80)	0.157 (1.85)
Log of population density of buildout area	0.141 (2.59)	0.125 (1.81)	0.142 (2.62)	0.110 (1.67)
Ten-year population growth, 1990-1999	2.152 (4.81)	2.167 (4.80)	1.886 (4.16)	1.916 (3.93)
Microwave links per hundred million people	1.146 (4.29)	1.070 (3.05)	1.258 (4.58)	1.102 (3.19)
Log of 1994 population	0.102 (2.27)	0.132 (1.46)	0.096 (2.14)	0.158 (1.91)
Fraction of households with annual income > $35k	-2.588 (5.30)	-2.560 (5.24)	-2.375 (5.11)	-2.315 (4.97)
Dummy = 1 if signaling bidder won either D or E license	**-0.503** **(5.82)**	**-0.472** **(4.02)**	**-0.334** **(3.53)**	**-0.269** **(2.20)**
Dummy = 1 if Sprint won either D or E license			0.321 (3.08)	0.321 (3.18)
Constant	-2.216 (6.18)	-2.177	-2.334 (6.13)	-2.253 (4.20)
Predicted value of the log of F-block price ($/pop)		0.109 (0.36)		0.224 (0.78)
Sample Size	493	493	493	493
R^2	0.500	0.555	0.513	0.605
Goldfeld-Quandt F-Statistic	2.428	1.238	2.470	1.280
numerator degrees of freedom	154	153	153	152
denominator degrees of freedom	154	153	153	152
p-value of Goldfeld-Quandt	0.000	0.094	0.000	0.065

Notes: Absolute values of t-statistics in parentheses, all t-statistics based on robust (White-corrected) standard errors, data is weighted by 1994 population.

Table 11: F-Block Regressions That Show Signaling Bidders Did Not Pay Less

	Log of F Price ($/pop)		
	OLS	2SLS	2SLS
Variable	(1)	(2)	(3)
Log of net C price ($/pop)	1.263	0.710	0.741
	(4.20)	(3.37)	(3.49)
Log of AB price ($/pop)	-0.061	-0.139	-0.135
	(0.38)	(0.88)	(0.86)
Cumulative number of bidders on F block in first 5 rounds	0.302	0.150	0.159
	(2.64)	(1.50)	(1.60)
Log of population density of buildout area	-0.007	0.000	0.000
	(0.08)	(0.00)	(0.00)
Ten-year population growth, 1990-1999	0.677	-1.217	-1.113
	(0.68)	(1.11)	(1.02)
Microwave links per hundred million people	0.576	-0.226	-0.182
	(1.44)	(0.55)	(0.44)
Log of 1994 population	-0.265	-0.375	-0.369
	(1.64)	(2.54)	(2.48)
Fraction of households with annual income > $35k	-1.101	2.009	1.839
	(1.58)	(2.05)	(1.88)
Dummy = 1 if signaling bidder won F license	**0.165**	**0.178**	**0.177**
	(0.71)	**(0.83)**	**(0.83)**
Constant	0.480	1.792	1.720
	(0.26)	(1.06)	(1.01)
Predicted value of the log of DE-block price ($/pop)		0.849	0.802
		(4.69)	(4.40)
Sample Size	493	493	493
R^2	0.297	0.504	0.512
Goldfeld-Quandt F-Statistic	1.619	1.181	1.262
numerator degrees of freedom	154	153	153
denominator degrees of freedom	154	153	153
p-value of Goldfeld-Quandt	0.001	0.152	0.076

Notes: Absolute values of t-statistics in parentheses, all t-statistics based on robust (White-corrected) standard errors, data is weighted by 1994 population.

Table 12: Price Differences Controlling for Market Attributes

	Not Controlling for Sprint		Controlling for Sprint	
	OLS	2SLS	OLS	2SLS
Bidder Type	(1)	(2)	(3)	(4)
Signaling	1.94	1.96	2.06	2.11
Nonsignaling	3.21	3.15	2.88	2.76
Price Difference	40%	38%	28%	24%

Notes: Signaling bidders are 21Century, AT&T, Mercury, NorthCoast, OPCSE, and USWest. Prices estimated by evaluating the estimated regressions at the population weighted means for variables other than dummy that indicates whether a signaling bidder won the license.

To test whether bidders who used signaling achieved favorable prices relative to other bidders, we estimate price regressions using a dummy variable for whether the markets were won by 21Century, AT&T, Mercury, NorthCoast, OPCSE, USWest.[21] The results for different specifications are given in Table 10 and Table 11. The estimated coefficients on this dummy variable are significant at the 5% level in all of the specifications for the DE price regressions given in Table 10, and are insignificant for the F price regressions given in all of the specifications given in Table 11. Just as with the average prices given in Table 9, the signalers achieved favorable prices on the D and E blocks, but not on the F blocks. An explanation for this might be that there was more competition on the F block: on average, four bidders fought for each F-block license, whereas, on average, five bidders fought for each pair of D and E block licenses. Just as the raw data indicates in Table 9, when including a dummy to mark off those licenses won by Sprint (results listed in the last two columns of Table 10), we see that Sprint did indeed pay more for the licenses than other nonsignaling bidders.[22] By including the Sprint dummy the coefficient on the signaling dummy variable diminishes, but is still significantly negative. Excluding the Sprint dummy variable may make the signaling bidders appear overly successful in achieving low prices.

[21] These five bidders won the following number of licenses: 21Century (10), AT&T (223), Mercury (32), NorthCoast (49), OPCSE (109), USWest (53).

[22] In fact, Sprint bid simultaneously for both the D and E blocks in many markets, indicating either a poor bidding strategy or a more inelastic demand than most bidders faced.

To make the price regression data more digestible, Table 12 predicts the prices for signaling and nonsignaling bidders using the results from the DE-block regressions. The log prices are predicted using the weighted means for all the variables except for the signaling bidder dummy variable, which correspondingly takes the value of 1 or 0, and then the log prices are exponentiated to give a dollar figure. These dollar figures should be used only to get an idea of the relative percentage differences for prices paid by signaling and nonsignaling bidders. The dollar figures and are not directly comparable with the raw data listed in Table 9, and can be considered underestimates of average prices paid since by Jensen's Inequality, finding the expectation of logged prices is less than the log of expected prices. However, the percent differences are comparable to that which can be calculated from the raw data in Table 9. Doing back of the envelope calculations, if we multiply 25% by the $3.58/person that nonsignaling bidders excluding Sprint paid, and then multiply this by the total population won in the D and E blocks by the signaling bidders (229.9 million people), we get just over $200 million. It is unclear, however, that this would be an appropriate measure of the losses, first since without retaliation it is unclear if these same bidders would win more or less population, and second since nonsignaling bidders may alter their strategies if they were not guarding against being punished.

Bidders did guard against bidding against AT&T, one of the retaliating bidders. In the DEF auction, AT&T won 223 licenses—more licenses than anyone else. These licenses covered 140 million people, over 50% more than any other bidder. To explore whether bidders avoided AT&T, we looked at all of the bids that occurred after round 10 on the D and E blocks in markets on which AT&T was the high bidder.[23] We ask the question: Did bidders bump AT&T when AT&T was the high bidder on the less expensive of the two blocks? If bidders did not care about the identity of the high bidder, they would arbitrage the prices of the D and E blocks, and bid against AT&T if the other block was more expensive. This did not happen. When the other block was 15% more expensive (the bidding increments were 5% or 10% of the standing high bid in the DEF auction), bidders still bid on the other block 32% of the time rather than bid against AT&T on the less costly block. When the other block was 25% more expensive, bidders still avoided AT&T 31% of the time. Even when the price of the other block was 50% higher, bidders bid on the higher priced block 27% of the time.

As a comparison, we performed this same exercise to see if bidders systematically avoided smaller bidders in the same way. We chose five bidders who won between 9 and 14 licenses—ACCPCS, Comcast, Rivgam, PAccess, and Touch. We counted all of the bids made by other bidders when one of these five bidders was the standing high bidder on the D or the E block. When the other blocks were 15%,

[23] AT&T, as a large bidder, was only eligible to bid on the D and E blocks in the DEF auction, since the FCC set aside the F-block licenses for small bidders.

25%, and 50% more expensive, bidders avoided these five bidders 20%, 18%, and 15% of the time, respectively. We summarize these results in Table 2.

Table 13: Do Bidders Avoid AT&T more than Small Bidders?

	AT&T	Five Small Bidders[1]	Test Statistic for Comparison of Means[2]
Other Block is 15% More Expensive			
Number of Bids on Other Block	194	28	
Number of Bids on Less Expensive Block	422	115	
Percent of Bids on Other Block	31.5%	19.6%	3.13
Other Block is 25% More Expensive			
Number of Bids on Other Block	140	16	
Number of Bids on Less Expensive Block	307	71	
Percent Bid on Other Block	31.3%	18.4%	2.75
Other Block is 50% More Expensive			
Number of Bids on Other Block	73	7	
Number of Bids on Less Expensive Block	203	41	
Percent Bid on Other Block	26.5%	14.6%	2.07

Notes:
[1]The five smaller bidders are ACCPCS, Comcast, Rivgam, PAccess, Touch, each of whom won between 9 and 14 licenses. AT&T won 223 licenses.
[2]Here, to get the test statistic, we assume that the decision to bid on the more expensive block follows a Bernoulli distribution. We then use the standard formula for comparison of means for two normally distributed random variables with unknown means and variances (Kmenta 1986, pp. 137 and 145). The test statistic is approximately normally distributed. The null hypothesis that the means are equal is rejected at the 5% level of significance in all three cases.

6 Conclusions

Even though the FCC has since drastically changed the auction rules in response to code bidding, it is likely that bidders can still use signaling in the form of retaliating bids to achieve the same sorts of coordination that code bidding accomplished. One interpretation of our paper:

- We detect code bidding and retaliating bids.
- We estimate direct revenue effects for these bidding and find close to zero effects.
- Yet the bidders who used these tools achieved very favorable prices relative to the other bidders.
- We conclude that it is likely that there are indirect revenue effects from having the tool to signal. The threat of signaling may deter competitive bidding.

To prevent such obvious signaling as code bidding the FCC has changed the rules towards click-box bidding, where after each round, for each license a bid increment is computed, and then bidders are constrained to bid the number of increments they wish to raise the bid. Thus, bidders are not choosing the trailing digits of their bids, and so cannot send signals to competitors/colluders. However, one of the things we had hoped to emphasize with out analysis is that this signaling can occur with retaliation that does not use trailing digits. It appears as if some bidders who experimented with code bidding, chose instead to use retaliations not containing trailing digits. The presence of such techniques can help coordinate market splits, collusive behavior, and can dampen revenues. Signaling bidders paid about 25% less than nonsignaling bidders on the D and E licenses, but paid about the same as nonsignaling bidders for F-licenses, which on average had much more competition. Though we take up more of the policy question and more discussion on auction design in Cramton and Schwartz (1999), one obvious policy interpretation that stands out from this paper is that stimulating competition is an effective guard against bid signaling. In this particular auction, competition could have been increased on the D and E licenses by extending the bidding preferences for small bidders to the D and E blocks, rather than restricting the preferences to the F block.

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