ESSAYS ON THE DESIGNATED ENTITY PROGRAM IN THE FCC FREQUENCY AUCTIONS

by

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Abstract

The Federal Communications Commission (FCC) has been auctioning frequency licenses since 1994. To encourage long-run competition in the telecommunication industry, the commission granted bid discounts to the small firms in its spectrum auctions. The primary focus of the dissertation is to evaluate the effect of the program on the number of licenses won by small firms, and on the FCC's auction revenues. It also examines the consequences of access manipulations by large-firm affiliates which used legal loopholes to capture over \$7 billion in discounts. The first chapter presents an overview of the FCC auction system and the discount program. It sets up the rest of the analysis. The second chapter of the dissertation applies a non-parametric estimation approach to recover the auction participants' value distribution through its bounds. Auction simulations using the distribution argue that the subsidy increases the share of small firm licenses from 25.9% to 27.6% at a low cost to the commission. They also imply that subsidy access by large firms has no significant effect on FCC's revenues but reduces the program's effectiveness by more than one third. The third chapter extends the analysis by introducing a parametric model that takes advantage of the bidder as well as license characteristics heterogeneity. My findings imply that perfect implementation of the program would triple the number of small firm licenses from 357, when no subsidies are present, to 942. It would also increase auction revenue from \$31.89 billion to \$34.17 billion. However, the access manipulations led to an increase in small firm licenses by just 266 for a total of 623, and a drop in FCC receipts to \$30.21 billion. The results of my dissertation suggest that improving the program's eligibility regulations holds benefits for both small firms and the FCC. Tightening the commission's access criteria would increase welfare.

Introduction

When Congress passed the Budget Reconciliation Act of 1993 it allowed the FCC to auction off its frequency licenses. Since the first round of auctions held the very next year, the commission has auctioned more than 5,500 licenses for over \$63 billion during the next 22 years. Because the initial auctions were dominated primarily by established large telecoms, the FCC attempted to provide support for small firms. The Designated Entity (DE) program was an attempt to provide more companies with access to the telecommunication markets and improve industry competitiveness in the long run.

Nevertheless, the subsidy also produced some unintended consequences - some large-firm affiliates managed to secure access to the program. Thus, some of the established telecommunication competitors gained an unfair advantage over their counterparts. The most notable case is the granting of a 25% discount to Dish Network, which subsequently used it to secure over half of the licenses auctioned in January 2015. Upon discovering the eligibility manipulation, many media outlets, as well as some economists, encouraged the FCC to discontinue the discount provisions.

This dissertation strives to highlight the effect of the DE discounts both under perfect implementation and when the program is undermined by large-firm affiliates. The first chapter provides an overview of the frequency auctions. It supplies the background information necessary to understand the auctioning mechanism applied by the FCC. It also explains the underlying issues which allowed for the legal loophole to be exploited by large firms.

The second chapter deploys a non-parametric approach which estimates the upper and lower bounds of the value distribution from which auction participants draw their values.

The bounds are then used to approximate the true distribution, and perform a counterfactual analysis. The alternative scenarios I explore are a world where the DE program is never present, as well as a paradigm where it is applied perfectly without any eligibility manipulations. The results of this analysis suggest that regardless of the program implementation, the FCC would increase the number of licenses won by small firms without encountering a revenue trade-off. If the program was removed, small companies would own 69 fewer licenses than they do under the current imperfect application. The number of licenses would decrease from 1,093 to 1,024. However, if there were no eligibility manipulations this number would increase by another 39 to 1,132 licenses held by DEs. This suggests that subsidy access by large-firm affiliates decreased its efficacy by a third.

The non-parametric estimation allows for licenses with similar observable characteristics to more heavily influence each other's value distribution bounds. This approach, however, does not provide significant insight about the bidding behavior of individual bidders or the significance of any given license characteristic. The third chapter of this dissertation remedies the issue by introducing a parametric approach to examine DE program efficiency and the effect of eligibility manipulations. It presents a reduced form linear model in the tradition of Paarsch (1997). While this framework imposes stricter distributional limitations, it also captures a higher degree of variation in license and bidder characteristics. The approach used in the second chapter relies on the highly restrictive bidder symmetry assumption. The design of the DE program implies that auction participants vary from one another, specifically in their size and financial capabilities. Thus, it may be more appropriate to waive the value distribution flexibility and account for bidder heterogeneity instead. Furthermore, the reduced form framework also captures the effect of license specifications.

The analysis performed using the parametric model provides a contrasting picture to its non-parametric counterpart in regards to auction revenues. The reduced form estimation suggests that when implemented in its current form the DE program reduces the FCC's collections from \$31.89 billion, when no subsidy is present, to \$30.21 billion. On the other hand, a perfect implementation of the program with no eligibility manipulations not only does not reduce the commission's receipts, but it even raises them to \$34.17 billion.

Considering the number of licenses won by small firms, the directions of the effects are similar, though the effects' scales are significantly higher under the regression analysis. Even when large firms access the subsidy program, the total number of auctions won by small firms would increase from 357, in the absence of auction discounts, to 623. If the DE program was perfectly implemented, the number of licenses acquired by small companies would increase further to 942.

The variance in the counterfactual results is a direct result of the differences in the applied models. The ability of the parametric framework to account for bidder heterogeneity allows it to capture aspects of the real world the non-parametric methodology cannot. This highlights the significance of estimation process choice, and the sensitivity of auction analysis to the degree of explained heterogeneity.

Leaving aside the argument about which methodology is superior, both of them predict an expansion in the set of small firm licenses. The first increase in number of licenses earned by small companies happens in the transition from a world with no subsidy to one where program manipulations take place. The second one occurs with perfect subsidy implementation. The two models, however, misalign in the magnitude of the change. The non-parametric estimation produces only a modest improvement for small firms. On the other hand, the reduced form analysis predicts doubling and tripling of the licenses held by small firms respectively with and without discount access exploitations.

The analysis results in chapter 2 and chapter 3 diverge further in respect to auction revenues. The second chapter of this dissertation suggests statistically insignificant losses of revenue when the current program is modified - both complete removal and eligibility restrictions. The parametric examination of the research questions indicates that access manipulations reduce auction receipts, but perfect program implementation may improve revenues.

These findings imply that when only true DEs are eligible for the program, the number of licenses small firms hold increases. Not only that, but the cost to the FCC is negligible at worst. At best, the commission gains from further restrictions to the DE program access. There is a potential for little or no trade-off between auction revenues and license redistribution towards small companies. My results argue against the calls for the program's closure, and support the FCC's efforts to continue restricting the access to the DE discounts. The program could be crucial in improving incumbents' service through increased long-run competition. It could also serve as a driving force behind innovation into the market through the inclusion of new companies which introduce better technologies.

Chapter 1

Industry Overview

1.1 Frequency Spectrum

Internet and phone services have become a critical and integral part of how modern society functions. The nature of the telecommunication industry, however, requires heavy regulation to maintain its quality of service. Unrestricted access to frequency bandwidth could lead to multiple entities using the same wavelengths, resulting in interference. To avoid this problem in the U.S., in 1981 the Federal Communications Commission began issuing spectrum licenses. The licenses grant their owners exclusive rights to a prespecified frequency bandwidth over a specific geographic area.

Initially the FCC distributed the licenses using comparative hearings where all interested parties presented their development plans and argued why they should be awarded the license. These hearings proved to be a sluggish process which awarded only 60 out of the available 1,468 licenses between 1981 and 1984. To expedite the process the FCC held lotteries for the rest of the licenses between 1984 and 1986. However, a randomized distribution of a finite resource, like frequency bandwidth, results in an inefficient allocation. Thus, while the comparative hearings may have allocated the spectrum to the companies which could make the best use of it, the lottery most certainly did not.

In an effort to improve the frequency distribution mechanism, Congress gave the commission the power to administer its own allocation system. The Budget Reconciliation Act of 1993 empowered the FCC to grant spectrum licenses through a series of auctions. This proved a quicker and more effective manner to distribute bandwidth rights. Furthermore, asking companies to outbid one another for the licenses increases the likelihood that the license winner is the firm that can extract the greatest value from the frequency.

Since the introduction of the auction system, the FCC has awarded more than 5,500 licenses to be used in the phone and internet industries. The total revenues of these frequency sales exceed $60 billion, adjusted for inflation. For all of its virtues, this distribution system suffers from at least one significant drawback. Because of the limited number of licenses larger, less financially constrained companies may foreclose smaller firms from acquiring frequency. A corporation with looser funding restrictions is less likely to be limited in the number and scope of licenses it can bid on. Spectrum rights acquisition is a necessary condition for any company to enter the market, and potentially expand to the level where it competes with the industry leaders. If smaller rivals were denied access to the market, the result would be reduced entry, and potentially evolution into a highly concentrated industry. To prevent this outcome the FCC attempted to encourage small firms to secure more licenses.

The commission implemented two policies to address these concerns. First, it administered set-aside auctions in which only small firms could participate. Second, it established the Designated Entity (DE) subsidy - winning bid discounts exclusively for small firms, firms managed by minorities or females, and rural telephone companies. The program grants qualified companies higher bidding power, as those firms pay only a portion of their bids when they win an auction. While both mechanisms succeeded in re-allocating more licenses towards small firms, the FCC reached the conclusion that the set-aside auctions decreased revenues more than the bid discounts. Thus, until 2015 the FCC used set-aside auctions once[1], whereas bidding discounts have been present in every auction since their introduction. The DE program, however, contained legal loopholes which threatened its integrity. Specifically, the eligibility criteria for a company to qualify for the program could be overcome by large-firm affiliates (LFAs) through a series of elaborate schemes.

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[1] The FCC used set-aside auctions for the initial distribution of the 493 licenses covering the 30 MHz frequency between 1895 MHz and 1910 MHz, and 1975 MHz and 1990 MHz. This series of auctions ended in 1996.

On multiple occasions LFAs obtained access to the DE discounts even though they should not have. Between 2000 and 2006 the FCC made three attempts to tighten the regulation and close the loopholes. Nevertheless, in 2015 another market leader, Dish Network, Inc., managed to secure a 25% bid discount through its subsidiaries. This particular eligibility manipulation brought the issue into the limelight. Where LFAs previously secured small numbers of licenses using the discount, Dish utilized it to capture more than half of the 1,611 licenses auctioned during the time it had access to the DE program. The total winning bids for Dish amounted to $13 billion, with $3.3 billion in discounts. The staggering amount of the subsidy sparked a discussion over whether the program should be discontinued. Ultimately, the debate led the FCC to impose a restriction in the total amount of allowed aid.

This paper explores in details the mechanisms used by the FCC to distribute frequency licenses in the telephone and internet markets. It describes what constitutes a frequency license, examines license characteristics in depth, and provides an overview of their main distribution mechanism - auctions. Additional attention is given to the Designated Entity program with its regulations, loopholes, and the aftermath of the recent eligibility manipulation.

1.2 Frequency Licenses

The FCC frequency licenses allow their holders to operate in a bandwidth spectrum within a designated geographic area. Because of the potential for frequency hoarding, the commission's approach has been to only auction frequency once the technology necessary for its utilization has been developed. Since the introduction of the licensing system, the FCC has introduced and auctioned new bandwidth four times. This tracks the transition from landlines to mobile devices, and later to 3G and 4G mobile data networks.

Table 1.1: Market Area Size Distribution

The measurement unit used to describe size is the number of counties included within a Market Area.

Variable	Obs	Mean	St. Dev.	Min	25^{th} p	Median	75^{th} p	Max
BTA	487	6.4497	6.1612	1	2	4	8	35
CMA	716	4.3869	3.0952	1	2	4	6	17
BEA	172	18.2616	14.9426	1	9	13	22	77
MTA	48	65.4375	45.4841	5	36	56.5	88.5	211
REAG	8	392.6250	303.7348	5	108.5	414	668	755

1.2.1 Market Areas

The FCC restricts every license it auctions to a certain geographic location called a market area (MA). The commission distributes licenses according to one of five possible different MA splits.[2] These splits vary in the number and the size of their MAs. Table 1.1 shows that the distribution with the least number of MAs, REAG, has 8 MAs with an average size of 392.6 counties per MA. Simultaneously, the split with the highest number of MAs, CMA, has 716 MAs with an average of 4.4 counties per MA.[3]

While there is no specific rule which relates license spectrum strip size to MA distribution, in the majority of the auctions the smaller the bandwidth block, the larger the MA size. This means that licenses for smaller spectrum sections are split into fewer MAs and give their holders access to a larger geographic area. Conversely, larger frequency strips are more restricted geographically and provide their holders with access to a smaller area. This bandwidth-MA distribution limits the possibility of frequency concentration and introduces incentives for companies to enter less profitable markets.

Suppose big frequency blocks covered large geographic areas. Such licenses would be very lucrative, but also highly valued. Since large companies have greater financial abilities, it is likely that predominantly big firms would end owning the licenses. Smaller local firms would be at a disadvantage if they could not finance the cost of acquiring a license. Simultaneously, if small licenses were sold over small MAs, certain areas would

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[2] Maps of all five MA splits are provided in the appendix. The distributions are Basic Trading Area (BTA), Cellular Market Areas (CMAs), Basic Economic Areas (BEAs), Major Trading Areas (MTAs), and Regional Economic Area Groupings (REAGs).

[3] These numbers reflect the number of MAs covering the territory of the 50 U.S. states and the District of Columbia. Numbers reported by the FCC include U.S. territories.

be unprofitable. Thus, few, if any, companies would be interested in acquiring small frequency blocks for rural, sparsely populated areas. People living in such regions would be left without telecommunication services. These are part reasons why the FCC sells larger bandwidths over smaller geographic areas, while smaller frequencies are auctioned for large MAs.

All MAs, irrespective of their distribution, consist of one or more whole census counties. However, within a single split, MAs do not overlap geographically with one another. In other words, within a specific MA split all counties on the territory of the U.S. are part of a MA and no county is a part of more than one MA. This frequency restriction guarantees that every frequency may only be operated by a single entity within a specific geographic location. Thus, license holders can provide service within their designated location and not interfere with other firms' transmissions.

1.2.2 Frequency Bandwidth

Each of the FCC licenses provides exclusive rights to only a single frequency block. For example, if a company wins a license for the AWS-3 block A1, it owns the rights to use any frequency between 1695 MHz and 1700 MHz over the specified geographic area. However, unless the company owns other spectrum licenses for the same geographic area, it is constrained to only transmit within that frequency range.

The frequency bands indicated for use by phone and internet companies are 824 MHz to 849 MHz, 869 MHz to 894 MHz, 1695MHz to 1780MHz, 1850 MHz to 1910MHz, 1930 MHZ to 1990 MHz, and 2110MHz to 2180 MHz. These bandwidths are split among 4 major standards - Cellular (CL), Personal Communications Services (PCS), and Advanced Wireless Services (AWS) 1 & 3. These standards reflect the innovations in the industry which enabled telecommunication companies to take advantage of higher frequencies. The bandwidth captured by the CL standard is 824 MHz to 849 MHz and 869 MHz to 894 MHz; PCS - 1850 MHz to 1910 MHz and 1930 MHz to 1990 MHz; AWS-1 - 1710 MHz to 1755 MHz and 2110 MHz to 2155 MHz; AWS-3 - 1695 MHz to 1710 MHz, 1755 MHz to 1780 MHz, and 2155MHz to 2180 MHz.

Table 1.2: Spectrum Blocks and Market Areas

In certain markets frequency block C could not be efficiently auctioned as a 30 MHz block. For that reason, in those market areas it was split into either two 15 MHz blocks, C-1 and C-2, or three 10 MHz blocks, C-3, C-4 and C-5. This split is reflected in the table where the frequency blocks C, C-1 and C-2, and C-3, C-4 and C-5 all cover the spectrum between 1895 MHz and 1910 MHz, and 1975 MHz and 1990 MHz

<table>
<tr><th>License</th><th>Channel Block</th><th colspan="4">Frequency(MHz)</th><th>Market Area</th></tr>
<tr><td>CL</td><td>A</td><td>824 - 835</td><td>845 - 846.5</td><td>869 - 880</td><td>890 - 891.5</td><td>CMA</td></tr>
<tr><td></td><td>B</td><td>835-845</td><td>846.5-849</td><td>880-890</td><td>891.5-894</td><td>CMA</td></tr>
<tr><td>PCS</td><td>A</td><td colspan="2">1859 - 1865</td><td colspan="2">1930 - 1945</td><td>MTA</td></tr>
<tr><td></td><td>B</td><td colspan="2">1870 - 1885</td><td colspan="2">1950 - 1965</td><td>MTA</td></tr>
<tr><td></td><td>C</td><td colspan="2">1895 - 1910</td><td colspan="2">1975 - 1990</td><td>BTA</td></tr>
<tr><td></td><td>C-1</td><td colspan="2">1895 - 1902.5</td><td colspan="2">1975 - 1982.5</td><td>BTA</td></tr>
<tr><td></td><td>C-2</td><td colspan="2">1902.5 - 1910</td><td colspan="2">1982.5 - 1990</td><td>BTA</td></tr>
<tr><td></td><td>C-3</td><td colspan="2">1895 - 1900</td><td colspan="2">1975 - 1980</td><td>BTA</td></tr>
<tr><td></td><td>C-4</td><td colspan="2">1900 - 1905</td><td colspan="2">1980 - 1985</td><td>BTA</td></tr>
<tr><td></td><td>C-5</td><td colspan="2">1905 - 1910</td><td colspan="2">1985 - 1990</td><td>BTA</td></tr>
<tr><td></td><td>D</td><td colspan="2">1865 - 1870</td><td colspan="2">1945 - 1950</td><td>BTA</td></tr>
<tr><td></td><td>E</td><td colspan="2">1985 - 1890</td><td colspan="2">1965 - 1970</td><td>BTA</td></tr>
<tr><td></td><td>F</td><td colspan="2">1890 - 1895</td><td colspan="2">1970 - 1975</td><td>BTA</td></tr>
<tr><td></td><td>G</td><td colspan="2">1910 - 1915</td><td colspan="2">1990 - 1995</td><td>EA</td></tr>
<tr><td>AWS-1</td><td>A</td><td colspan="2">1710 - 1720</td><td colspan="2">2110 - 2120</td><td>CMA</td></tr>
<tr><td></td><td>B</td><td colspan="2">1720 - 1730</td><td colspan="2">2120 - 2130</td><td>EA</td></tr>
<tr><td></td><td>C</td><td colspan="2">1730 - 1735</td><td colspan="2">2130 - 2135</td><td>EA</td></tr>
<tr><td></td><td>D</td><td colspan="2">1735 - 1740</td><td colspan="2">2135 - 2140</td><td>REAG</td></tr>
<tr><td></td><td>E</td><td colspan="2">1740 - 1745</td><td colspan="2">2140 - 2145</td><td>REAG</td></tr>
<tr><td></td><td>F</td><td colspan="2">1745 - 1755</td><td colspan="2">2145 - 2155</td><td>REAG</td></tr>
<tr><td>AWS-3</td><td>A-1</td><td colspan="4">1695 - 1700</td><td>EA</td></tr>
<tr><td></td><td>B-1</td><td colspan="4">1700 - 1710</td><td>EA</td></tr>
<tr><td></td><td>G</td><td colspan="2">1755 - 1760</td><td colspan="2">2155 - 2160</td><td>CMA</td></tr>
<tr><td></td><td>H</td><td colspan="2">1760 - 1765</td><td colspan="2">2160 - 2165</td><td>EA</td></tr>
<tr><td></td><td>I</td><td colspan="2">1765 - 1770</td><td colspan="2">2165 - 2170</td><td>EA</td></tr>
<tr><td></td><td>J</td><td colspan="2">1770 - 1780</td><td colspan="2">2170 - 2180</td><td>EA</td></tr>
</table>

Each of these standards consists of frequency blocks - strips of frequency with a combined size of either 5MHz, 10 MHz, 15 MHz, 20 MHz, 25 MHz or 30 MHz.[4] CL contains two equally sized blocks of 25 MHz labelled A and B. PCS is constructed of three 30 MHz blocks and three 10 MHz blocks - the larger strips are labelled A, B, and C, while the smaller ones are denoted D, E, and F. Furthermore, because one of the 30 MHz blocks, C, could not always be auctioned efficiently, the FCC split it into two 15 MHz blocks (C1 and C2). In certain areas a further split was necessary which led to distributing the block

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[4] Multiple non-consecutive frequency strips could be contained within a single block. While Advanced Wireless Service-3 block A-1 contains a single frequency strip, Cellular block A contains 5 separate bandwidth strips.

in three 10 MHz blocks (C3, C4, and C5). AWS-1 consists of three 20 MHz strips (A, B, and C) and three 10 MHz blocks (D, E, and F). Finally, AWS-3 contains a 5 MHz block (A1), three 10 MHz strips (B1, G, H, and I), and a 20 MHz block (J). Table 1.2 contains a summary of the standards and the frequency blocks, as well as their physical locations in the spectrum.

When selling previously unauctioned bandwidth, the commission sells all licenses for the respective spectrum covering the entire territory of the U.S. For any secondary offering of licenses the FCC groups previously unsold licenses together. In both cases I refer to the collection of license auctions as an auction set. The commission has labeled all such auction sets by their consecutive numbers. For example, the first PCS auction set which offered frequency blocks A and B was labeled as auction set 4 because it was the 4^{th} set of frequency auctions administered by the FCC. The first three provided frequency best suited for radio communication which is not part of the current study.

1.3 Auctioning Mechanism

The frequency distribution relies on a series of ascending auctions - participants place bids in an attempt to outbid one another. In particular, the FCC applies simultaneous multi-round auctions. In that process a collection of auctions is administered simultaneously - all auctions begin and end at the same time. The approach allows companies to internalize license complementarities, and effectively acts as a substitute to combinatorial bidding. Thus, the burden of determining whether the value of a collection of licenses is higher than that of all the individual licenses is shifted from the auctioneer to the participants.

Furthermore, auctions are performed in a series of rounds during which companies may place bids on any set of licenses they deem profitable. The only requirement is that within a round all bids placed on a certain license must exceed the maximum bid on that license in the previous round. This restriction, however, does not force companies to outbid the highest bid within the current round. As a result all participants willing and able to bid in the current round can do so. Unlike regular ascending auctions where each bid must always improve on the previous bid, the commission's mechanism allows all bidders to place similar bids simultaneously. This enables auction participants to continue bidding until they cannot outbid the maximum bid from the previous round. Thus, bidders are more likely to place their final bids closer to their true values than they would in an incremental bidding auction.

The mechanism of the commission's simultaneous multi-round auctions allows participants to place their bids during the round. At the end of each round the commission makes public the highest bids for each license along with the identification codes of the firms which placed them. Thus, between rounds participants can re-evaluate their strategies and determine the most appropriate future course of action. The FCC does not specify a predetermined number of rounds within which the auctions end. Instead, it allows auctions to continue so long as there is at least one bid placed on any of the auctioned licenses. Thus, even if there has been no activity in an auction for a number of rounds, firms are still allowed to improve on the highest bid. If there are no bids on any of the auctioned licenses, the bidding process concludes.

As in most ascending auctions, in spectrum auctions the highest bid is deemed the license winner. Nevertheless, because of the round bidding it is possible for multiple companies to place the same winning bid within a round. In that case the firm that placed its bid first is declared the auction winner.

1.4 Designated Entity program

Although this auctioning mechanism alleviates the need for combinatorial bidding, a substantial flaws was under-representation of small firms among the license winners. This phenomenon decreases the number of companies which can potentially enter the market, likely lowering the industry competitiveness and leading to higher concentration levels. Highlighting the importance of this issue, a study by the Open Technology Institute indicates that small firms are the primary drivers of innovation and service quality improvement (Russo and Morgus, 2014). This led the commission to search for a policy which would encourage small firms to compete more effectively with larger firms.

To diversify frequency ownership the FCC tested two support schemes. The set-aside auctions where only small companies could bid, and winning bid discounts which allowed selected enterprises to only pay a fraction of their official bid. The FCC concluded from these tests that while both approaches provide small companies with more licenses, the set-aside auctions severely restricted the auction collections. Thus, the commission adopted the DE program which provides participants with certain levels of average annual revenue (AAR) over the last three years with significant bid discounts. Specifically, the FCC created three categories of DE discounts:

1. Companies which earned between \$15 million and \$40 million in AAR over the last three years qualify for 15% discount
2. Companies which earned between \$3 million and \$15 million in AAR over the last three years qualify for 25% discount
3. Companies which earned less than \$3 million in AAR over the last three years qualify for 35% discount

The regulation imposed by the commission states clearly the size of the discount and the thresholds a firm must meet to qualify. The only ambiguity in the definition stemmed from the revenue calculation mechanisms. As stated above the rules did not explicitly prohibit contractual relations between a DE and a large competitor. Thus, nothing prevented the main telecommunication corporations from establishing new subsidiaries which would qualify for the subsidies as they would have no revenues. To avoid this the FCC introduced a revenue calculation framework which defined the companies whose revenues were used in the final AAR computation.

Many small local telecoms rely on their larger counterparts for out-of-service-area roaming. As a result there exist numerous contracts between parties that could become DEs and those which are not targets of the program. That complicates the differentiation between true small firms and large-firm affiliates when the FCC calculates the DE eligibility AAR. Consequently, since the introduction of the program in 1998, the commission has revised its AAR computation regulation four times - in 2000 and 2003, and twice in 2006 (Title 47 CFR 1.2110 [63 FR 2343, Jan. 15, 1998; 65 FR 52345, Aug. 29; 2000, 68 FR 42996, July 21, 2003; 71 FR 6227, Feb. 7, 2006; 71 FR 26251, May 4, 2006]). In each instance the commission extended the set of contractual relationships which require a firm's revenues to be included in the AAR calculation for a subsidy status application.

Despite the efforts of the FCC to restrict opportunities for eligibility manipulations, Dish Network, Inc. accessed the program through its subsidiaries for the auctions ending in January 2015. Dish associates managed to secure over half of the offered licenses with bids totalling \$13 billion. As the FCC had granted the company's affiliates 25% discounts, Dish was set to avoid paying over \$3 billion. Following a public backlash the commission revoked its subsidy which led Dish to give up some of the licenses it won in order to keep its total bids under \$10 billion. While this was certainly not the first time a large firm has taken advantage of the program, no firm had applied it on such a scale. In the aftermath, certain scholars in the field questioned whether the program should continue operating (Brake, 2015). However, the FCC decided not to close the program and instead review and revise the eligibility regulations (FCC, 2015a; FCC, 2015b).

1.5 Subsidy Discussion

The recent denouncement of the FCC's Designated Entity program is based on the direct effects of introducing subsidies into the market place. Examining the direct merit of redistributing licenses towards smaller companies is questionable. The auction outcomes' economic efficiency decreases as the winner of the frequency auctions are not necessarily the firms which value the offered licenses the most. Moreover, it is possible for firms which would have won the auction even without the program to pay a lower procurement price because they qualified for the discounts. These concerns are the basis for the argument to eliminate the subsidy program.

These arguments present the direct losses of administering a subsidy program in an auction setting, and overlook the potential gains of the indirect effects. The loss of static efficiency in terms of license allocation could lead to dynamic efficiencies through the increased long-run competitiveness of the industry. In the presence of more small firms, the telecommunication markets are less likely to evolve into concentrated oligopolies. This diminishes individual companies' market power, and could potentially lead to lower prices and better service for consumers.

Even if we disregard the potential improvements of the competitive environment in the industry, introducing a subsidy could lead to increases in the commission's revenues. Economic theory does not provide a definitive conclusion on the effect of subsidies in ascending auctions. The main reason is that the presence of programs such as the winning-bid discounts under specific circumstances could force the license winner to pay a higher procurement price. Because of this uncertainty predicted by theoretical research, it is imperative to examine the effects of the subsidy in the FCC auctions empirically. That is the primary objective of this dissertation.

The secondary objective of this study addresses a problem that is not directly introduced by the presence of the DE program, but is rather its by-product. Under flawless implementation a DE discount could benefit both the FCC, and the general public. However, as evident from the events of January 2015, eligibility manipulations have been a continuous issue surrounding the program. Uncovering the effect of the subsidy program is a complex task on its own. Untangling it from the consequences of access misuse further complicates the problem. Thus, the work I present in the following chapters aims to pinpoint the effect of the bid discounts, as well as evaluate the consequences of large firms wrongfully qualifying for the program.

Chapter 2

The Effect of Designated Entities Subsidies in the FCC Spectrum Auctions

2.1 Introduction

Since it started auctioning spectrum the FCC has auctioned over 5,500 frequency licenses for a total of over $60 billion. The majority of these licenses, which serve as barriers to entry, were secured by several large companies. This raised concerns with the resulting license allocations. In an attempt to improve the competitiveness of the final market, the FCC adopted a policy granting bid discounts to designated entities (DEs). The objective of the subsidies is to ensure more small firms earn exclusive rights to frequencies which would increase the long-run competition opportunities in the industry. The recipients are formally defined in the Fifth Memorandum Opinion and Order (FCC 94-285) as “small businesses, businesses owned by members of minority groups and/or women, and rural telephone companies.” Nevertheless, affiliates of large firms such as AT&T and Dish Network found gaps in the eligibility criteria through which to take advantage of the discounts.

The bidding process in these auctions can be modeled as a game between auction participants. As such, the optimal bidding strategy for a firm is a best response function to its rivals' values. The presence of bid discounts can alter the auction outcomes since the discounts act as inflators of eligible firm values. When the subsidy recipient does not win the auction, it may still force the winner into offering a higher procurement price in order to outbid all other participants. The chain reaction started by the presence of a subsidy suggests that the program could influence the auction results in two ways. It could either lead to a different, subsidized auction winner, and potentially provide the auctioneer with less revenue, or it could result in the same winner placing a higher bid to procure the license.[1] This juxtaposition creates ambiguity about the effect of the subsidy program on auction revenues and outcomes, and requires knowledge of bidder values and discount eligibility for a thorough examination of the program's effects.

When all discount recipients are small firms, the primary potential drawback is the revenue loss the FCC suffers to provide the program. However, unintended access to the subsidies challenges the efficacy of the program in achieving its goal to redistribute licenses. As more large firm affiliates take advantage of the legal loopholes, the effect of the subsidy is reduced and the status quo is re-established. If access to the subsidies is exploited, does the presence of discounts still result in more small firms winning a frequency license? How much revenue does the FCC forego to provide the program? How many licenses are taken by large firm affiliates due to the subsidy access manipulation and how does it affect auction revenue?

In addition to revenue reduction, subsidy eligibility manipulations can significantly impede industry evolution and restrict progress in service quality and affordability (Russo and Morgus, 2014). For example, the development of gigabit networks in Kansas, Missouri, and Tennessee by new providers gave users the opportunity to obtain higher speed internet service at lower prices. The fastest connection provided by these new competitors reaches 1 gigabit, and the plans cost less than \$150. In comparison, the quickest plans AT&T and Verizon provide in metropolitan areas like New York and Los Angeles have a maximum speed of 500 megabits. These plans are not only slower, but also cost over \$300. The contrast in these characteristics suggests that the presence of small firms could direct

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[1] A simple example of how the presence of subsidies affects auction outcomes is discussed in section 2.2 of the paper.

the telecommunications industry towards providing both cheaper and faster service.

My study of spectrum allocation utilizes data from the FCC auction records. The files contain information on the gross and net bids placed by all participants in all auctions administered by the commission. Through them I can deduce whether a firm qualifies for a bid discount even if it does not win the auction. Knowing the participants bidding behavior and observing whether they receive a subsidy provides a rich dataset with which to estimate the value distribution and evaluate the effectiveness of the program.

I apply the non-parametric framework described by Haile and Tamer (2003) which estimates upper and lower bounds for the value distribution of auction participants. The approach is based on the behavior assumptions that 1) no participant bids above its value, and 2) no bidder lets a rival win at a price it is willing to outbid. Using the bound estimates I approximate the true value distribution from which I draw bidder valuations, and then I simulate the baseline auction outcomes. To assess the subsidy program's success, I simulate the auction results with all bid discounts eliminated. This provides a counterfactual paradigm where bid discounts are not present. Then, I manually identify whether companies are actually small firms or are affiliates of large corporations. Then, I simulate the auction outcomes for a world where the subsidy program is implemented without any eligibility exploitation.

My findings suggest that there is no decrease in FCC revenue from the subsidy program. When all bid discounts are removed, the number of small firms which win auctions on average decreases by 69 from 1093 to 1024 (6.3%), and there is a slight negative effect on auction revenues. Thus, the subsidy program does not impose a trade-off between the number of licenses granted to small firms and the FCC auction receipts. When subsidies are restricted, so that only truly small firms can receive them, the number of auctions won by small firms increases by 39 to 1132 (3.6%). This scenario also results in lower auction revenues. These findings are similar to the results from the study on the Canadian timber auctions by Athey, Coey, and Levin (2011).

My paper is the first to examine the FCC spectrum auctions by following the idea of Athey, Coey, and Levin (2011) to estimate the effects of a subsidy in auctions. However, their study only considers the presence of a perfectly regulated subsidy in which all recipients are truly eligible for assistance. The main deviation from that framework is that I examine the effect of subsidy access manipulations. I explore the effects from firms being erroneously granted access to the program. The economics literature on auctions predominantly assumes flawless implementation of proposed policies in its analyses. Nevertheless, it is reasonable to expect large companies will attempt manipulations to obtain assistance not designed for them. The side-effects of such behavior on a policy goal are an important aspect which economics research rarely addresses. My work concentrates on these unintended consequences and how they alter the DE program outcomes.

The rest of the paper is divided into six sections. Section 2.2 provides a brief literature review. The industry and the effect of subsidies in ascending auctions, are described in section 2.3. Section 2.4 describes the data used in this paper, while section 2.5 summarizes the methodology developed by Haile and Tamer (2003). The results are presented and discussed in section 2.6. Section 2.7 concludes, and provides possible paper extensions.

2.2 Literature Review

This is the first paper in the economic literature which examines empirically the effect of manipulations of the auction subsidy program, to my knowledge. Nor is there any research examining the effect of the bid discounts granted by the FCC in the frequency auctions. Furthermore, this is among the few studies, along with Athey, Coey, and Levin (2011), which explore the consequences of subsidies in ascending auctions. The main advantage of my work is the lack of assumptions about the form of the value distribution. Following the methodology described in Haile and Tamer (2003) I do not need to impose a specific distribution family from which the firm values are drawn.

This paper follows two primary topics in the economics literature. Firstly, it relates to the studies on aid programs in auctions such as Krasnokutskaya and Seim (2011) and Marion (2007). Their research explores the effect subsidies and set-aside auctions have on auction outcomes, cost of procurement, and auction participation in California highway construction auctions. One of the main differences between my work and theirs is that they examine first-price sealed-bid auctions, whereas I focus on ascending auctions. The other distinction is that their papers consider only perfect implementation of the subsidy programs, while I explore the potential for misconduct from subsidy manipulations.

Another work on subsidy programs is Loertscher and Marx (2014) who study efficiency in the presence of subsidies and secondary markets. The literature also includes Hyndman and Parmeter (2011) who study the efficiency of the subsidy. Other studies related to firm aid in auctions are Nakabayashi (2013) who examines Japanese public construction projects, and Kim et. al (2012) who discuss an experimental design exploring the role of set-aside auctions.

My work also contributes to the FCC frequency bandwidth auctions literature. The field started with the summary of McMillan (1994) which explores the similarities between spectrum auctions and the California gold rush. McAfee and McMillan (1996) provide theoretical support for the use of SMR auctions as an efficient license allocation tool. Research on the spectrum auctions also reviews auction performance. Fox and Bajari (2013) study the distribution of licenses. They suggest that offering four large regional licenses instead of the actual 493 licenses will increase allocative efficiency by 48%. Yeo (2009) examines the bid mark-ups in FCC auctions and finds a large distortionary effect in the form of informational rents in the auctions.

The bidder behavior as a result of a sequence of Bayes-Nash equilibria is the idea developed by Hong and Shum (2003). Their idea develops the formation of prices as a best response to other auction participants given the information disclosed at the end of each round. The major drawback of their framework is the conditioning on observed bidding behavior. That limits to applicability of the methodology as it cannot be used to perform counterfactual analysis.

Cramton and Schwartz (2002) examine the potential for collusive behavior by auction participants. Using their methodology, Rose (2007) evaluates the persistence of collusive behavior in FCC auctions. He applies the estimation approach to a dataset from the latest round of FCC auctions. The findings in Rose (2007) suggest that collusive signalling by bidders remains an issues even after having been identified by Cramton and Schwartz (2002).

The papers discussed so far examine various effects of FCC auctions - their efficiency, potential rents, and bidding behavior. One of the few aspects that has not been evaluated is whether the subsidy program is successful. That is the main contribution of this paper to the literature on FCC auctions. My work also investigates the effects of subsidy access manipulation - an important aspect of bid discounts application that has not been studied in detail.

2.3 Telecommunications Spectrum

2.3.1 Licenses and Subsidies

Operating a mobile phone and internet services business requires the acquisition of a spectrum license. The access to frequency bandwidth is essential as it allows the wireless transmission of information. The license grants its holder access to a specific frequency band over a certain geographic area.[2] The licensing system presents the potential for large corporations to foreclose their smaller rivals from entering the market. In an attempt to address this issue the FCC introduced the DE subsidy.

The program undoubtedly improved the odds of small firms securing spectrum licenses. Nevertheless, its loose eligibility criteria have allowed large firms to qualify for the subsidy despite multiple attempts by the FCC to close the loopholes. This phenomenon eventually led to calls for ending the program. The main argument of critics of the discount is that subsidizing auction participants inevitably leads to a loss of revenue. They also argue that this loss does not outweigh the provided benefit to small firms, so that the program is not worthwhile.

The argument that revenue is lost holds with respect to subsidized firms that win auctions. Regardless of whether the company would have won the license absent the DE program, the commission's revenues are lower in such cases when the discount is present. However, this is only one possible scenario when subsidies are used. Other scenarios do

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[2] Additional discussion on the bandwidth strips and geographic areas applied when issuing licenses is included in the appendix.

not result in reductions in the FCC's earning. In fact, under certain conditions, it could even be financially beneficial to the commission to subsidize bidders.

2.3.2 Subsidy Effects

Subsidies in an auction would decrease of revenues *ceteris paribus*, i.e. no company changes its behavior. There are two possibilities when no company changes its bid. If the auction winner does not receive a subsidy, the amount the FCC collects is unaffected. Alternatively, if the auction winner secures a subsidy, the commission collects a smaller amount due to the bid discount. When participants' bids are static in the presence of subsidies, the amount collected by the FCC will be at most the same in each auction, though it could be smaller. Therefore, the only effect a subsidy could have on revenue collections is to decrease them.

However, bids are the outcome of a strategic interaction between auction participants. In an ascending auction every participant continues bidding until its value is lower than the current bid. The FCC subsidies - bid discounts - are equivalent to value inflators which may change the bidding and the auction outcome. A company which receives a subsidy may not necessarily win the auction, but it could push the winner's bid higher, and consequently increase the license equilibrium price. Thus, when taking into account the bidding behavior with the introduction of subsidies, the net effect becomes ambiguous.

To demonstrate the above statement, consider an auction with three participants. For the purposes of the example assume that these bidders are named AT&T, Verizon, and T-Mobile. AT&T values the auction at $\$100,000$, Verizon has a value of $\$90,000$, and T-Mobile of $\$72,000$. In this scenario there is an opportunity to receive a 25% subsidy. A firm receiving the subsidy will pay only 75% of the bid, if it wins the auction. Without subsidies, AT&T can win the auction with a bid of $\$90,000$, and the auctioneer will receive $\$90,000$. If AT&T receives the subsidy, it still wins the auction with a bid of $\$90,000$, but the FCC will collect $\$67,500$ instead of $\$90,000$.

The auction revenues also decrease if instead Verizon receives the subsidy. The auction winner changes and auction collections are higher than the case where AT&T received the subsidy. Because Verizon only pays 75% of its bid, it can win the auction with a bid of $\$100,000$. Even though the bid exceeds Verizon's value, the actual amount that it will pay, $\$75,000$, which is below its value. Thus, if Verizon receives the subsidy, it will win the auction with a higher bid, but make a lower payment. The auction revenues will be lower than when no subsidy is present, but higher than had AT&T received the subsidy.

Finally, if T-Mobile receives the subsidy, AT&T wins the auction, but it pays $\$96,000$. The reason is that T-Mobile is willing to bid up to $\$96,000$, higher than AT&T's final bid of $\$90,000$ when there were no subsidies. Since T-Mobile doesn't pay the full amount, it would only have to pay 75% of $\$96,000$ which is its license value - $\$72,000$. When T-Mobile receives the subsidy, it still cannot win the auction, but it forces the winner to pay a higher amount than in the no subsidies case.

None of the three firms whose names were used in the above example is small enough to qualify for the discounts, either on its own merit or through its subsidiaries. However, the example shows that depending on the subsidy recipient, the auction revenue may vary significantly. The only case in which revenue collections do not decrease is when a firm with substantially lower initial value receives the subsidy. In such a case the revenue collections may increase due to the presence of a winning bid discount. Nevertheless, in the instances where the subsidized firm's value is so low it remains below the second highest value even when inflated, the auction revenues remain the same.

The above discussion depicts the ambiguity of bid discount subsidies. It proves that from a theoretical perspective there are no grounds to argue that the DE program is necessarily detrimental to the commission's revenues. Thus, it is imperative to examine the effect of such subsidies in the FCC auctions. The lack of a simple theoretical framework which can unambiguously predict the overall effects calls for an empirical approach.

2.4 Data

The data used in this paper is from the FCC frequency auctions between 1995 and 2015. Upon the completion of an auction set the commission publishes the bidding records

Table 2.1: License per Auction Participant

The table summarizes the number of licenses per auction participants in mobile telecommunication auctions.

Auction Number	Frequency Block	Number of Bidders	Number of Licenses per Auction Participant
Auction set 5	PCS C	255	1.93
Auction set 11	PCS D, E, & F	143	10.34
Auction set 45	CL	7	0.43
Auction set 66	AWS-1	160	7.01
Auction set 77	CL	2	0.50
Auction set 97	AWS-3	63	25.62

on its web-site. These records contain all the bids placed by all the firms for frequency bandwidth licenses, in every round of every auction. This rich dataset provides the highest bid all participants placed in the examined time period. The commission tracks the bidder and license identities, the market area, the strip size and range, and both the gross and net bid auctions. The difference between the last two, if there is any, is the bid discount the FCC granted.

Controlling for the characteristics of market areas requires demographics information. I utilize county demographics population size data provided by the U.S. Census. As market areas consist of whole counties, combining the population of individual counties yields the market area population. I match auction sets to demographics data from the year preceding the auction as that is more likely to correspond to the informations firms take into account when evaluating a license. For example, if an auction is held in 2006, I match the licenses in that auction set with the demographic data from 2005 for the covered market area.

There are 12 auction sets relevant to this study - their numbering as per the FCC nomenclature is 5, 10, 11, 22, 35, 45, 58, 66, 71, 77, 78, and 97. The 12 are the only ones which offer licenses used by telecommunication companies for the transmission of phone and internet services. However, 6 of the auction sets contain unreliable information. These are the auction sets which re-auction licenses sold in previous auctions and ones for which the initial license holder defaulted on their payments. Some of the companies which defaulted on their payments filed for bankruptcy, and demanded the FCC not to revoke their licenses. The commission, nevertheless, revoked the licenses and later re-auctioned them. Eventually, these cases were brought to the Supreme Court, where the bankrupt firms won, and kept the licenses. For that reason I consider the FCC files for those auction sets containing such licenses unreliable and drop them form the data.

From the remaining six auction sets, one is dropped because it was restricted exclusively to small firms. Smaller companies have lower purchasing power, and may value licenses lower than large firms. As a result, the value distribution estimated using that auction set may be biased towards smaller values, resulting in smaller auction valuations. Of the remaining auction sets, two have significantly fewer bidders per license than the other four auctions. The differences are summarized in Table 2.1. The reason for that is this auction contains licenses which are being re-auctioned. Thus, firms have better information about the license value, and possibly bid more aggressively. To avoid issues from the possible change in behavior, I remove this auction set from the final sample.

The result of the data selection is the use of 3955 auctions out of the full sample's 4928. An overview of firms' bids in the remaining auctions suggests that there is a significant difference between firms which qualified for 15% and 35% discounts compared to companies with no discounts. Nevertheless, firms which qualified for 25% subsidies bid in a similar fashion to firms with no subsidies and unlike firms with other subsidies. Table 2.2 shows that is the case both for the total sample, and when it is split into winning and non-winning bids. This suggests there is an unusual bidding behavior among the 25% subsidy recipients. Furthermore, a table in Appendix E shows that this phenomenon holds across all auction sets included in the final sample, and is not specific to any individual set.

Analyzing the effect of bid discounts access manipulation requires differentiation between subsidy recipients into two groups - small firms, and large firm affiliates.I distinguish members of the two groups on a case by case basis. Starting with the full set of subsidy-receiving companies, I research each to discover whether it had any ties to a large firm. The search includes reviewing ownership records, whenever available, and news article mentioning ties between entities involved in the auctions and established telecommunication firms. The independence of a subsidy receiver is based on the lack of evidence

Table 2.2: Bids by Subsidy Allocation ('000s of dollars)

The table summarizes the bids measured in '000s of U.S. dollars. All sections contain information on license auctions with at least 2 bidders in FCC auction 11, 66, and 97. Section A contains statistics on the highest bids placed by a company in auctions 11, 66, and 97. Section B contains statistics on just the winning bids, and section C contains the information on the non-winning bids.

Variable	Obs	Mean	St. Dev.	Min	Max
Variable	Obs	Mean	St. Dev.	Min	Max
A. All Bids					
Total	18,679	12,899.04	78,399.99	0.00	2,762,964.00
No subsidy	10,702	13,815.98	78,394.95	0.00	2,762,964.00
15% subsidy	564	773.60	1902.64	0.10	25,546.00
25% subsidy	7,406	12,509.62	81,298.81	0.01	2,712,964.00
35% subsidy	7	0.01	0.00	0.00	0.01
B. Winning Bids					
Total	3,955	15,416.88	91,367.43	2.01	2,762,964.00
No subsidy	2,393	18,894.86	104,960.00	2.01	2,762,964.00
15% subsidy	152	609.61	917.89	9.90	5,481.33
25% subsidy	1,410	11,110.42	68,273.67	8.40	1,315,700.00
35% subsidy	0	-	-	-	-
C. Non-Winning Bids					
Total	14,724	12,222.73	74,522.46	0.00	2,712,964.00
No subsidy	8,309	12,353.26	68,808.08	0.00	2,362,964.00
15% subsidy	412	834.11	2,153.06	0.10	25,546.00
25% subsidy	5,996	12,838.65	84,070.89	0.01	2,712,964.00
35% subsidy	7	0.01	0.00	0.00	0.01

connecting it to a large company.

I summarize the result of identifying subsidy manipulating firms in Table 2.3. Applying this information to the data, I observe that the number of companies that manage to manipulate the discount access in their favor is relatively stable. However, the number of licenses won by those firms in the latest auction set is significantly greater than in any previous occasion. In auction sets 11 and 66, the large firm affiliates which qualified for bid discounts collected around a quarter of the total licenses won by 25% subsidy receivers. In comparison, that increases to over 85% for auction 97. That may be one of the reasons why the issue with the policy manipulation has not received much attention until recently.

Another explanation why not much attention has been given to the effect of subsidy access manipulations is the number of licenses collected by individual firms. Table 2.4 suggests that in the first two auctions, the number of licenses collected by large firm affili-

Table 2.3: Subsidies Received

The table summarizes auction participants and outcomes data. Section A focuses on the number of firms active in the auction and their separation based on firm type. Section B reports the number of licenses won by firms divided by company affiliation. Section C reports the auction set revenues and the amount of the provided subsidies.

	Auction set 11	Auction set 66	Auction set 97
A. Auction Participants by Allocation Status			
Total	143	160	63
Small firms	95	97	32
Big firm affiliates with subsidies	4	3	4
Big firms affiliates without subsidies	44	60	27
B. Licenses Won by Allocation Status			
Total	1455	924	1576
Small firms	435	152	115
Big firm affiliates with subsidies	91	23	826
Big firms affiliates without subsidies	929	749	635
C. Auction Outcomes			
Auction Revenues (billions of \$)	3.6	16.2	40.9
Auction Subsidies (billions of \$)	0.3	0.2	3.6

Table 2.4: Auctions Won by Subsidy Allocation

The table summarizes the distribution of licenses collected for all participants that won at least one auction. All section report the results by firm type. Section A pertains to auction set 11, section B - to auction set 66, and section C - to auction set 97.

	Obs	Mean	St. Dev.	Min	Max
A. Auction set 11					
Total	119	12.2	28.4	1	213
Small firms	85	5.1	6.2	1	44
Big firm affiliates with subsidies	3	6.7	3.2	3	9
Big firms affiliates without subsidies	31	32.3	50.0	1	213
B. Auction set 66					
Total	95	9.7	23.3	1	135
Small firms	53	2.9	3.1	1	16
Big firm affiliates with subsidies	2	11.5	4.9	8	15
Big firms affiliates without subsidies	40	18.7	33.9	1	135
C. Auction set 97					
Total	29	54.3	100.9	1	345
Small firms	13	8.8	12.4	1	40
Big firm affiliates with subsidies	4	206.5	161.9	16	345
Big firms affiliates without subsidies	12	52.9	87.8	1	250

ates was comparable to that of unaffiliated small firms. Thus, the companies bending the rules and taking advantage of the legal loopholes are not easily recognized. The difference occurs when subsidy-receiving firms collect as many licenses as a large company.

The take-away from the data is that subsidy access manipulations have persisted since the introduction of the program. Nevertheless, firms that managed to circumvent the discount-granting criteria initially attempted to partially match the behavior of the true DEs. It was not until the latest auction set that big firm affiliates demonstrated bidding activity similar to other large companies and attracted attention to the problem.

2.5 Methodology

Investigating the effect of eligibility manipulation requires the recovery of the true value cumulative distribution function (CDF). I apply the approach developed in Haile and Tamer (2003) which takes advantage of the value ordering for auction participants. The relationship between bids and bidder values allows me to determine upper and lower bounds for the true value CDF. I then use the average of the two bounds to estimate of the true CDF. The true distribution is a weighted average of the bounds, but as I have no prior beliefs about which bound is closer to the distribution in terms of absolute distance, I use equal weights.

An alternative approach that is sometimes applied in the literature is the use of individual bids as the true value of the bidder which placed it. The main shortcoming of this approach is that companies may not be able to bid their exact valuations due to requirements for increments that are multiples of a specific minimum bid increment. In such cases, the company will likely place a bid that is smaller than its value, and drop out of the auction if any competitor bids a higher amount. Thus, the econometrician does not observe the companies' true values, and assuming the bid as such creates an upward bias in the CDF estimates.

The probable CDF bias is the key reason for using the Haile and Tamer (2003) framework. In addition, when the researcher has no prior knowledge on the value distribution, which is the case in this paper, imposing a distributional form may alter the results. Hence, I follow the established practice in the literature on ascending auctions and apply this method (Hortacsu and McAdams (2010), McAdams (2008), Kastl (2006)).

2.5.1 Assumptions

The estimation approach is based on two assumptions regarding bidding behavior of the auction participants.

1. No company bids above its valuation for the license auctioned.
2. A firm willing to beat a certain bid will not let another firm win the auction at that bid.

It is important to note that while the authors do not explicitly state it, those two assumptions impose a truth-telling equilibrium. There might be other equilibria in which firms overbid on some license in order to exhaust their competitors funds for other licenses. To avoid such a dynamics, which would complicate the model, I impose the truth-telling equilibrium as well.

The estimation procedure I use requires the use of the Independent Private Value Paradigm (IPVP). Using the IPVP framework limits the model in several important respects:

- All licenses are homogeneous in every characteristic
- All auction participants are identical

To accommodate the first assumption, I split the sample into 45 different sub-samples. The split is based on the population size of the market area, and the exact frequency strip covered by the license. I differentiate three market population sizes: small - less than 50,000 people; medium - between 50,000 and 250,000 people; large - more than 250,000 people. In terms of frequency strip the FCC designates 15 different bandwidths to which license holders could gain access. The result of these two criteria is the partition of the full sample into 45 sub-samples containing auctions for relatively homogeneous licenses.

This paper does not address the second estimation limitation. An extension which controls for the possibility that small and large firms may draw their values from different distributions is discussed later in this chapter.

2.5.2 Relating Auction Participants Values and Bids

The non-parametric model in Haile and Tamer (2003) has the advantage of not specifying any distributional form. It also does not depend on predetermined bidding functions, which allows for a higher level of bidding behavior complexity. To compensate for the lack of a strict relationship between the realized values and bids, the framework considers observed bids and unobserved values as the realizations of two separate random variables.

When considering the bids data, Haile and Tamer (2003) denote $b_{i:N}$ as the i_{th} lowest bid when N auction participants are present. It is taken to be the realization of the random variable $B_{i:N}$. The distinction between the bids of the 1st, 2nd, etc. lowest bids is necessary, as those bids behave as though they are drawn from different distributions. The set of all the lowest bids in all auctions with N participants is going to have a distribution which reaches its maximum at a much lower value than the set of all the highest bids. The same notion holds for the license values as well. That requires the definition of $V_{i:N}$ as the random variable for the participant with the i_{th} lowest product value out of N. Its realization is denoted as $v_{i:N}$. The relationship between $V_{i:N}$ and $B_{i:N}$ is used to determine the upper bound, while the relationship between $V_{N-1:N}$ and $B_{N:N}$ serves as the base for the derivation of the lower bound.

Assumption 1 translates into the notion that the i^{th} lowest bid cannot exceed the i^{th} lowest value. If the i^{th} lowest bid exceeds the i^{th} smallest value, then there would be at least one company among those first i firms, that placed a bid above its product valuation. Since that is assumed impossible, it has to be the case that the i^{th} lowest bid cannot exceed the i^{th} lowest value. Mathematically, this claim reflects the following system of inequalities

$$b_{i:N} \leq v_{i:N}, \forall i \in \{1, ..., N\} \tag{2.1}$$

A notable characteristic of this construction is that there is no requirement for the bidder with i^{th} lowest valuation to place the i^{th} lowest bid. Imposing the restriction that the firm with $v_{i:N}$ is the one which placed $b_{i:N}$ will yield tighter bounds as demonstrated by Chesher and Rosen (2015). Nevertheless, given the observed behavior patterns, where companies would bid in an auction and then not improve on its bid for several rounds despite rivals outbidding it, this assumption may be too stringent for the FCC auctions.

A consequence of equation (1) is the first-order stochastic dominance of $V_{i:N}$ over $B_{i:N}$. Let $F_{i:N}(v)$ denote the Cumulative Distribution Function (CDF) of $V_{i:N}$, and $G_{i:N}(b)$ as the CDF of $B_{i:N}$. If $b_{i:N} \leq v_{i:N}$ for any possible pair of realizations $b_{i:N}$ and $v_{i:N}$, then it has to be true that for any values v that satisfy $F_{i:N}(v) > 0$, it has to be true that $G_{i:N}(v) = 1$. In other words, $G_{i:N}(.)$ is deterministically dominated by $F_{i:N}(.)$, which is a sufficient condition to prove the stochastic dominance of the value distribution over the bid distribution. That guarantees that

$$F_{i:N}(v) \leq G_{i:N}(v), \forall v \in \mathbb{R}, i \in \{1, ..., N\} \tag{2.2}$$

This result provides an upper bound for the ordered value distribution based on the observed distribution of bids. However, the focus of the researcher is the bounds of the value distribution from which all values are drawn, and not the ordered value distributions. If all ordered value CDFs $F_{i:N}(v)$ are based on a parent distribution CDF $F(v)$, Arnold et. al(1992) proves that $F(v)$ is uniquely identified.

The uniqueness proof is based on the existence of a monotonic differentiable transformation $\phi(.; i, N)$ such that $F(v) = \phi(F_{i:N}(v); i, N)$. This transform-ation implicitly solves for the parent distribution of a certain ordered statistic of rank i out of N. It is uniquely identified due to the monotonicity of both $F(v)$ and $F_{i:N}(v)$. That makes $\phi(F_{i:N}(v); i, N)$

a one-to-one function which returns the implicit solution of the equation [3][4]

$$F_{i:N}(v) = \sum_{r=i}^{N} \binom{n}{r} \phi^{r} (1-\phi)^{n-r} \tag{2.3}$$

Haile and Tamer (2003) use the property of the monotonic transformation $\phi(.;i,N)$ to derive

$$\phi(F_{i:N}(v);i,N) \leq \phi(G_{i:N}(v);i,N), \forall v \in \mathbb{R}, i \in \{1,...,N\} \tag{2.4}$$

As $\phi(F_{i:N}(v);i,N) = F(v)$, equation (4) simplifies to

$$F(v) \leq \phi(G_{i:N}(v);i,N), \forall v \in \mathbb{R}, i \in \{1,...,N\} \tag{2.5}$$

The framework applies a similar approach to determining the lower bound of the value distribution. To use assumption 2, let Δ denote the minimum bid increment for auction participants. That translates auction estimation assumption 2 as

$$v_{i:N} < b_{N:N} + \Delta, \forall i \in \{1,...,N-1\} \tag{2.6}$$

If there is a company with a valuation higher than the winning bid, and it is capable of beating the winning bid by a higher placing bid with at least the minimum increment, then that company would improve on the winning bid and win the auction. As no company beats the winning bid, it has to be the case that no company's valuation is as big as the minimum increment added to the winning bid. Moreover, because by definition $v_{1:N} \leq v_{2:N} \leq ... \leq v_{N-1:N}$, transitivity implies that $v_{N-1:N} < b_{N:N} + \Delta$ is a sufficient condition for $v_{i:N} < b_{N:N} + \Delta, \forall i \in \{1,...,N-2\}$. That eliminates the need to solve the full system

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[3] A discussion on ordered statistics and the derivation of the ordered statistics formula is contained in appendix B

[4] Equation (3) provides the discrete form representation of the ordered statistic formula. It also has a continuous form representation:

$$F_{i:N}(v) = \frac{N!}{(N-i)!(i-1)!} \int_{0}^{\phi} s^{i-1} (1-s)^{N-i} \, ds$$

of inequalities in (6) and simplifies it to

$$v_{N-1:N} < b_{N:N} + \Delta \tag{2.7}$$

Similarly to the derivation of equation (2), the deterministic dominance of the incremented bid distribution over the value distribution yields

$$F_{N-1:N}(v) \geq G^{\Delta}_{N:N}(v), \forall v \in \mathbb{R} i \in \{1, ..., N-1\} \tag{2.8}$$

where $G^{\Delta}_{N:N}(.)$ is the CDF of $B_{N:N}+\Delta$. Applying the distribution transformation $\phi(.; i, N)$ to equation (8) and simplifying it yields

$$F(v) \geq \phi(G^{\Delta}_{N:N}(v); N-1, N), \forall v \in \mathbb{R}, i \in \{1, ..., N-1\} \tag{2.9}$$

Equations (5) and (9) yield a collection of upper and lower bounds. To get tighter bounds, Haile and Tamer (2003) suggest taking the minimum of the upper bounds at every point. Since the value CDF is smaller than any of the upper bounds, it is also smaller than the minimum of those bounds. For the upper bound, the authors recommend taking the maximum of the minimum bounds. That results in the following system of inequalities

$$F(v) \leq \min_{N \in \{2,...,\bar{N}\}, i \in \{1,...,N\}} \phi(G_{i:N}(v); i, N) \tag{2.10}$$

$$F(v) \geq \max_{N \in \{2,...,\bar{N}\}} \phi(G^{\Delta}_{N:N}(v); N-1, N) \tag{2.11}$$

The systems of inequalities (10) and (11) provide upper and lower bounds which can be estimated non-parametrically. Taking the theoretical model to the data requires the derivation of the bid distributions from the observed placed bids which yields the following estimation framework:

$$\overline{F}(v) = \min_{N \in \{2,...,\bar{N}\}, i \in \{1,...,N\}} \phi(G_{i:N}(v); i, N)$$

$$\underline{F}(v) = \max_{N \in \{2,...,\bar{N}\}} \phi(G^{\Delta}_{N:N}(v); N-1, N)$$

$$G_{i:N}(v) = \frac{1}{T_N} \sum_{t=1}^{T} 1(n_t = N, b_{i:N} \leq v)$$

$$G^{\Delta}_{N:N}(v) = \frac{1}{T_N} \sum_{t=1}^{T} 1(n_t = N, b_{N:N} + \Delta \leq v)$$

where $\underline{F}(v)$ and $\overline{F}(v)$ are respectively the lower and upper bound of the distribution of the auction values; n_t is the number of participants in auction t; T is the total number of auctions; T_N is the number of auctions with N bidders, $T_N = \sum_{t=1}^{t} 1(n_t = N)$.

This estimation approach relies on the independent private value paradigm (IPVP). As such it cannot take into account the possible complementarities between licenses. A company can hold licenses for the same bandwidth across neighboring market areas, or for physically neighboring frequencies for the same market. In both cases acquiring more than one license increases that particular company's value for the individual licenses. Thus, the values of the licenses could be correlated which is a violation of the IPVP. Therefore, this methodology cannot take into account any license complementarities. This will bias the estimated value distribution down, as the approach may assign a higher probability to a value that is inflated due to interdependencies.

2.5.3 Calibrating the model to the data

The estimation procedure requires the definition of a minimum bid increment(MBI). The FCC applies a mixture of criteria to determine the MBI. The initial condition is that the MBI is 10% of the highest bid placed for the license in the previous round of the auction. The commission also adjusts the MBI dependent on the bidding activity for the license. Those refinements depend on parameters defined by the FCC for each auction separately but not disclosed to the econometrician. Thus, I use the 10% increment as the only standard for the MBI.

After establishing the MBI, I derive the bid distribution $G_{i:N}(.)$ and incremented bid distributions $G^{\Delta}_{i:N}(.)$ from the data. Applying numerical integration, I implicitly solve for the distribution transformations $\phi(.; i, N)$ using the binary search algorithm.[5] The transformed distributions are then implemented in the upper and lower bounds estimations. The average of the two bounds is utilized as an approximation of the value distribution itself. In practice, any weighted average of the two bounds could be the true value distribution. Since I have no prior belief of which bound is closer to the true distribution, I weigh the two equally in the final step of the approximation process.

2.6 Results

2.6.1 Estimation Results

The estimation results for the auctions of licenses for the frequencies between 1890 MHz and 1895 MHz and from 1970 MHz to 1975 MHz are displayed in Figure 2.1.[6] The three plots support the claim that telecommunication firms put higher value on markets with larger populations. The graphs suggest that the auction value distributions shift right as market size increases. This result aligns with the findings of Yordanov (2014) that firm entry depends on market size but not on demographic characteristics. This result is intuitive as the companies will cater to any client able to pay for their services. As cellular and internet services are essential and relatively inexpensive, that opens the market to the whole population regardless of individuals' race, gender, or age. The only demographic characteristic entering a telecommunication company's profit function is the size of the market - the total population of the serviced market area.

The graph in Subfigure (b) also shows that the bounds can get extremely close to one another. In some cases the bounds are not only close, but in fact they intersect. This phenomenon is acknowledged by Haile and Tamer (2003), who find its cause in the concavity of the minimum function and the convexity of the maximum function. To prevent the bounds from intersecting, the authors recommend that they are smoothed by the use of a weighted average.[7]

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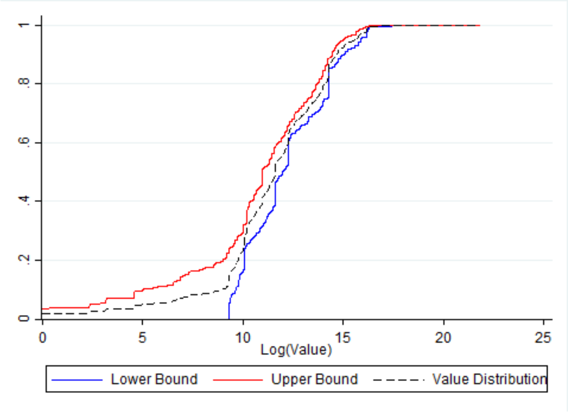
[5] A detailed description of the binary search approach is placed in the appendix C.

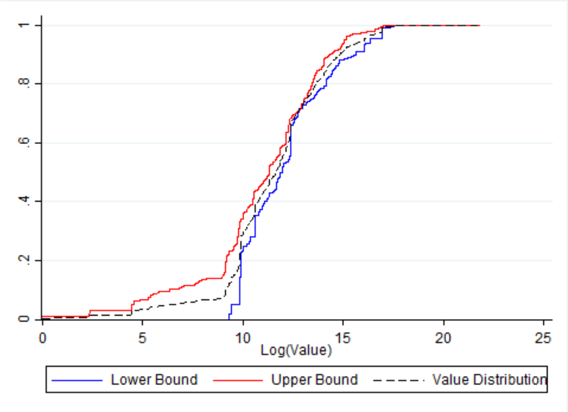
[6] The estimation results for other frequencies are included in the appendix E.

[7] The exact boundary smoothing procedure is described in appendix D

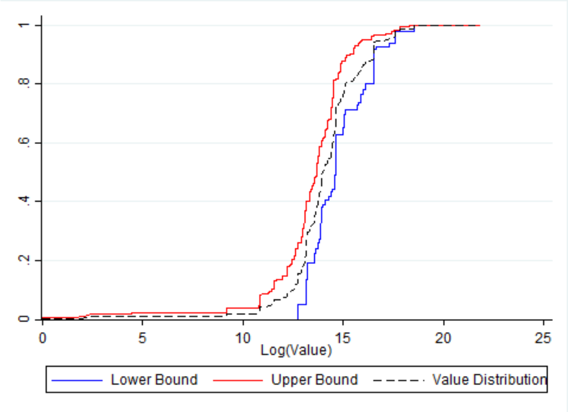
Figure 2-1: Market-Size Estimation Results, PCS Block F



(a) Small Market



(b) Medium Market



(c) Large Market

Nevertheless, splitting the full sample into 45 sub-samples and smoothing the bounds still leaves 32 cases in which the estimated upper and lower bounds intersect with one another. As the upper bound should not be smaller than the lower bound, it is evident that the technique applied in this paper is insufficient to control for the auction heterogeneity present in the sample. Additional solutions to this problem are addressed in a later section of the paper where I discuss an extension proposed by Haile and Tamer (2003) which may solve the issue.

2.6.2 Counterfactual Results

An important remark to the methodology is that because the estimation procedure is based on bid rankings, I utilize the gross bids in the estimation. When I examine the counterfactual policies, I require the net values for some of the bidders involved in the auctions, so I discount the simulated values by the subsidy size for which the firms qualified. I denote $\hat{V}$ as the vector of all simulated values and $\tilde{V}$ as the vector of all net values. The relationship between the two can be expressed as

$$\tilde{V} = \hat{V} \cdot (1 - S)$$

where S is a vector with elements equal to 0%, 15%, 25%, or 35%. The actual value is determined by the size of the firm's discount. If a firm does not qualify for a subsidy, its corresponding elements of S are equal to zero.

To simulate the auction results, I draw values for all auction participants from the estimated value distribution. Based on the assigned valuations I record the company with the highest value as the license winner and its bid as the second highest value. The FCC collections are calculated as the sum of all winning bids less the subsidy, wherever applicable. I also record whether the auction winner is a small firm.

For the baseline scenario I maintain subsidy eligibility as observed in the FCC spectrum auction records. The simulation results suggest that my estimation provides results similar to those observed in the real world. The simulated auctions generated 1093 small firms winning spectrum auctions. The resultant auction revenues amount to $71.19 billion, and subsidies of $8.99 billion. Those figures are higher than, though relatively close to, the real world: 700 auctions won by small firms, $57.03 billion of auction revenues, and $7.74 billion of subsidies.

In addition to the baseline case, I simulate the outcomes of all 3955 auctions in the data sample for the two counterfactual scenarios. As discussed earlier in the paper, I keep auction participation and subsidy qualification fixed. The only variable I shift is the access to subsidies for firms in the sample. First I remove all subsidies to evaluate the overall effectiveness of the program. Then, I limit access to the discounts to only true DEs to measure the effect of large firms manipulating their eligibility for the program. The results from the counterfactual analysis are reported in Table 2.5 which displays the change in selected outcome variables with respect to the baseline case. The focus of my analysis is the number of licenses that small firms win in the auctions, the revenue collected by the FCC, and the amount of subsidies awarded by the commission.

Removing All Subsidies

Removing all subsidies requires the use of only gross auction values. When calculating the auction collections and distributed subsidies I regard all companies as ineligible for bid discounts. Imposing the subsidy program is expected to increase the number of frequency licenses acquired by small firms at the expense of the commission's auction revenues. The results provide evidence that the availability of spectrum indeed improves for small companies, but there is no decrease in the FCC revenues.

My findings suggest that the FCC auction receipts experience a slight increase in the presence of the subsidy program. When all bid discounts are removed, the number of small firms which win auctions on average decreases by 69 from 1093 to 1024. That is a 6.3% decrease in the number of small firms winning a license. In terms of penetration, the fraction of small companies which won licenses decreased by 1.7 percentage points from 27.6% to 25.9%. It also has a slight negative effect on the auction collections. The decrease is economically small - $650 million over all 3 auctions. Compared to the

Table 2.5: Counterfactual Results

The table reports the results of the performed counterfactual analysis. The average number of licenses held by small firms in the simulated real world is 1093. The average net revenue from the auctions is $71.19 billion, and the average subsidies amount to $8.99 billion. The changes in auction revenues and generated subsidies are measured in billions of $. All coefficients are reported with the respective 95% confidence interval in parenthesis.

	No Subsidies	Limited Subsidies
Change in number of licenses won by small firm	- 69	+ 39
	(-85, -53)	(+27, +53)
Change in net auction revenues	-0.65	-0.82
	(-2.12, +0.79)	(-2.09, +0.49)
Change in generated subsidies	-8.99	-4.81
	(-10.60, -7.57)	(-6.13, -3.80)

simulated revenues of $71.18 billion, that is a decrease of less than 1%. The change in revenue is nonetheless statistically insignificant as the 95% Confidence Interval (CI) in billions of dollars is $(-2.12, .73)$.

These results imply that the commission does not face a direct trade-off in its decision to offer bid discounts in its spectrum auctions. This is not to suggest that the FCC is definitively better-off offering the program as my estimates do not take into account any administrative costs. However, so long as the additional expenditure associated with maintaining the program does not exceed $600 million, the FCC's net revenue does not decrease.

My findings are supported by the existing literature as other studies have discovered that the introduction of target subsidies may improve auction revenues. Athey, Coey, and Levin (2011) find suggestive evidence that this effect is present in the Canadian timber auctions. Their study focuses entirely on the benefits of a subsidy program as a superior option to both set-aside auctions and the status quo. This paper explores not only the benefits of the subsidy program, but also the consequences of access manipulation by large firms.

Limiting Subsidies to True DEs

Examination of the effect of erroneous bid discounts eligibility requires comparison of the baseline case and a paradigm where only true DEs are allowed to the program. When the bid discounts are only accessible by actual small firms, I use net values for large firm affiliates when replicating auction outcomes. Similarly to the first counterfactual, I am interested in the increase of revenues due to tightening the access to subsidies. The main difference is that with only small firms qualifying for the discounts I expect the number of licenses earned by DEs to increase.

The simulation of the auctions indicates that while the number of auctions won by small firms does increase, FCC auction receipts decrease. Limiting the access to the subsidy program does not diminish the commission's proceeds, and it may even benefit them. The results show a decrease in the auction revenues of $815 million. While the amount is larger than when all subsidies are removed, the result is still statistically insignificant - the 95% CI expressed in billions of dollars is $(-2.09, .67)$.

This result is in stark contrast with opinions expressed by media outlets regarding the losses imposed by large firms on FCC revenues (Gryta, Knutson, and Ramachandran, 2015). The primary complaint is that large corporations are extorting funds from the government that could be applied towards public projects. My findings suggest the opposite. Instead of appropriating billions of dollars from society, the misconduct by large companies which exploited legal loopholes raised the overall auction revenues. Consequently, the FCC auction receipts benefit from the subsidy access manipulations.

In terms of auctions that small firms won because of large firm affiliates being denied access to the discounts, there is an increase of 39 licenses that change hands in favor of DEs. That increases the number of license held by small companies from 1093 to 1132. The penetration of DEs in license holding increases from 27.6% to 28.6%. Comparing between the two counterfactuals, the presence of subsidies for small firms only increases the penetration rate by 2.7 percentage points. The access manipulating firms decrease the effect by 1 percentage point which is equivalent to a reduction of the subsidy program goal by more than one third.

2.6.3 Robustness

When choosing the MBI I noted that the FCC has a set of criteria for determining the actual MBI. Some of those criteria depend on coefficients used by the commission, but not disclosed. Hence, I cannot perfectly predict the auction MBI, which introduces possible measurement error into the estimation.

As a control for this phenomenon I examine the data for the bid increments between the winner and the second highest bidder. Those are the most likely candidates for the minimum bid increment as imposed by the FCC. The data provides a rich set of bid increments in both absolute and percentage terms. For that reason I perform the estimations and counterfactual analysis using multiple values for the MBI.

In particular, I consider the 5^{th} and 95^{th} percentile bid increment in percentage terms. In addition to the main specification where $\Delta = 10\%$, I also use MBIs of 0% and 33%. The results from both the estimation procedure, and the simulations are mostly unchanged. The changes in outcome variables are similar and the analysis conclusion remains valid. Hence, I consider the 10% MBI specification to provide results robust to the specification.

2.7 Final Remarks

2.7.1 Future extension

The methodology applied in this paper has several drawbacks. The first one is that despite the attempted control for auction heterogeneity, the upper and lower bounds still intersect for 32 of the estimated sub-samples. As the issue persists, a possible solution to the problem is outlined by Haile and Tamer (2003). They suggest that value distributions be estimated for each individual auction. This approach would require weighing each auction observation by a kernel product based on the auction characteristics - license specifications and market area demographics. Currently, all observations receive the same weight.

After correcting for the auction heterogeneity, it is still possible that bidder asymmetry may pose a problem. Using the set-aside auction set I discarded from the sample would provide an opportunity to overcome this issue. While, those auctions may bring bias to an overall estimation, they isolate small firms on their own. It should be possible to use the set-aside to estimate the small firm value distribution, and then use that distribution to estimate the value distribution for the large companies.

2.7.2 Overview and Limitations

The FCC frequency auctions have distributed over 5,500 exclusive licenses for spectrum. In an attempt to encourage competition in the telecommunications markets, the commission established the DE subsidies to help small companies gain access to scarce bandwidth. Utilizing legal loopholes large firms gained eligibility for the discounts and received an advantage over their competition.

This paper examines the effect of subsidy program and the consequences of access manipulation. My understanding is this is the first study to explore the topic. Applying a non-parametric estimation procedure which pinpoints an upper and a lower bound on the true value distribution, I recover the value CDF. I simulate the auction participants license values and replicate the auction outcomes, including the license winner identities and the magnitude of the winning bid.

The results from the counterfactual analysis suggest that the FCC revenue does not decrease due to the subsidy program, and it may actually grow. Either eliminating the subsidies altogether or limiting them to only the intended DEs results in lower auction receipts. Eliminating all the bid discounts decreases the number of spectrum grants to small firms. On the other hand, limiting the access to just small firms increases the number of licenses secured by small companies.

The primary conclusion is that the subsidy program does not present a trade-off to the FCC. The commission increases the attainability of licenses for DEs without losing revenue. Additionally, I find that the manipulation of legal loopholes by large firm affiliates financially benefits the commission while reducing the number of licenses held by small firms.

One of the primary limitation of this study is the strong assumption of firm symmetry. While separating large from small firms alleviates the problem, it does not provide a complete solution. Asserting that Verizon, AT&T, Sprint, T-Mobile, and Dish are similar to smaller companies which are still too big to be classified as small would be incorrect. Thus, the current methodology does not allow for sufficient level of bidder heterogeneity.

Treating all non-small companies as identical could lead to overstating mid-size firms' values, or understating those of large corporations. This qualifies the results from this study and calls for further examination using an improved methodology. One potential solution is to limit the flexibility of bidder value distributions but allow for firm differentiation. This could be achieved using a reduced form linear model. This alternative approach to the current research questions is the focus of the next chapter of this dissertation.

Chapter 3

A parametric approach to examining the Designated Entity program in the FCC frequency auctions

3.1 Introduction

The Designated Entity (DE) program in the Federal Communication Commission's (FCC) frequency auctions strives to improve long-term competitiveness in the telecommunication industry. It encourages small companies to gain access to the scarce broadband by providing them with winning bid discounts. However, the program has been criticized heavily during the past year and a half due to eligibility manipulations by large-firm affiliates (LFAs). Despite the FCC revising its program access criteria thrice, Dish Network qualified for a 25% discount at the latest round of frequency auctions in January 2015. With combined winning bids worth $13 billion, Dish was set to evade paying over $3 billion for the licenses it secured. This prompted the FCC commissioner Ajit Pai to call for further restrictions on the parties eligible for the program. Some analysts, including Doug Brake from the Information Technology and Innovation Foundation, went even further requesting that the program be discontinued (Brake, 2015).

The parties opposed to the DE discounts principally argue that the program is financed solely by tax payers. This motivates a detailed examination of the source of the program's funding - whether the financial transfer to subsidized entities is from the FCC or, potentially, other auction participants. The focus of the current study is not only verifying whether the DE discount leads to more small firms winning license auctions, but also uncovering the cost to the commission of implementing the DE program. Additionally, this paper emphasizes the effect of eligibility manipulations by LFAs. Particular interest is paid to the number of licenses that would have been won by small firms if there were no LFA manipulations, as well as the change in the auction revenues.

The analysis utilizes the rich auction data provided by the FCC records. The records hold information about the individual bidders and their bidding behavior in every single auction in which they participate, as well as the bidder's subsidy status. The license market characteristics are constructed using the Census county level demographics data. The combination of these sources results in a panel dataset which includes bidder and market characteristics for every bid placed in the FCC auctions.

I construct a reduced form parametric framework which takes advantage of the observable firm and license characteristics to examine the research questions. This methodology manages to explicitly take into account the differences between the bidders, and among the auctioned licenses. The counterfactual analysis used to answer the questions is based on the main assumption in Benkard, Bodoh-Creed and Lazarev (2010). Specifically, I assume that conditional on observable characteristics firms do not change their bidding behavior regardless of whether they are receiving the DE discount or not. This specification allows me to construct each firm's bid as a function of license value primitives, as well as firm specific characteristics, including subsidy status. In the counterfactual scenarios I set all firms' subsidy status to 0 when I assess the effect of the program. To evaluate the effect of eligibility manipulations, I remove the subsidy status only for LFAs.

The parametric analysis provides support for the hypothesis that the DE program has a significant impact on small firms in acquiring frequency licenses. The result holds irrespective of whether there are eligibility manipulations - the number of license won by small firms increases from 357 to 623 under the current program. That number increases further to 942 licenses if the program is implemented perfectly and only true DEs have access to the discounts. Thus, eligibility manipulations decrease the program's effectiveness in securing more licenses for small firms by half. Perfect implementation of the DE discounts leads to 585 more licenses earned by small companies, whereas when LFAs get access to the program the number is only 266. The cost of providing the program with its current shortcomings is over \$1 billion. This is a result of the decrease in simulated auction revenues from \$31.89 when there are no DEs to \$30.21 billion after the subsidy is implemented. Additionally, the discount access exploitations lead to auction revenue decrease by almost \$4 billion - from \$34.17 under perfect implementation to \$30.21 billion when LFAs have access to the program. These numbers together suggest that if the program was implemented perfectly - no LFA eligibility manipulations - the FCC would collect an additional \$3 billion dollars.

The findings support the claim by program opponents that the eligibility manipulations hurt tax payers. Nevertheless, if the program eligibility problems are resolved, there is potential for higher auction collections than if the program is not present. Unlike LFAs, DEs do not predominantly win the auctions in which they participate. So, instead of paying discounted amounts to secure a license, true DEs force auction winners to place higher bids and increase the equilibrium price of the licenses. As a result the commission's auction revenues do not plummet, but in fact grow to a higher level. Thus, it may be in the best interest of both the FCC and small firms for the commission to close the loopholes in its regulation, rather than abolish it.

This is the first parametric study on the effect of the DE program and its eligibility manipulations on the FCC frequency auction outcomes of which I am aware. Its findings on the effect of the perfectly implemented DE program are similar to the non-parametric analysis used in Yordanov (2015). However, unlike Yordanov (2015) this paper finds a decrease in revenue when the program is implemented with the eligibility manipulations. This deviation is a product of the difference in the used methodologies. The current analysis likely produces results that are closer to the true counterfactual outcomes as it better accounts for license as well as bidder characteristics. While Yordanov (2015) incorporates to a certain extent license heterogeneity, its evaluation relies heavily on bidder symmetry - an extremely restrictive assumption.

Beside the policy implications, this paper is among the first to examine the unintended consequences of introducing a program with flexible eligibility criteria. The restrictive nature of the frequency licenses have created an environment in the telecommunication industry where small companies rely heavily on interaction with large firms. This poses a great challenge in properly identifying the truly small firms which should be granted the subsidy status. As a result, the regulation chosen by the FCC has left significant loopholes which are exploited by LFAs. The main contribution of this paper is in examining the unanticipated effects of the subsidy eligibility manipulations in terms of revenues and number of licenses won by small firms.

The rest of the paper proceeds in the following fashion: Section 3.2 overviews the relevant economic literature; Section 3.3 provides a brief description of the FCC auctions, the DE program, and its effect on auction outcomes; Section 3.4 discusses the data used in the analysis; Section 3.5 proposes a parametric model used to estimate competitors bidding functions; Section 3.6 presents the estimation results and the counterfactual analysis; Section 3.7 concludes the paper.

3.2 Literature Review

This work relates to the broad collection of studies dedicated to the FCC frequency license auctions. The most notable avenues explored by previous papers are the presence of collusion in the placed bids, and the determinants of bidder behavior. The first line of research includes the works of Cramton and Schwartz (2002) and Rose (2007). These studies examine the FCC auctions in search of evidence of bidder collusion. Both of them use the methodology developed by Cramton and Schwartz (2002) but on different subsets of the FCC auctions. The findings of both works suggest that bidders were collaborating in the examined auctions. These findings provide an important insight into the auctioning system. Nevertheless, the authors of either paper do not suggest any applied framework which practitioners could use to simulate the auction environment when performing counterfactual analysis. This is a limitation of the literature as incorporating bidder collusion may significantly influence auction outcomes in terms of the relationship between a firm's bid and its value.

In the second line of FCC auctions research, scholars concentrate on establishing new methodologies through which to deconstruct the bidding process. The most notable works include Haile and Tamer (2003) which provides a non-parametric bounds approach to estimating value distribution bounds, and the game-theoretic model developed in Hong and Shum (2003). For the purpose of the current analysis I am unable to apply either of those techniques. Given the rich dataset at my disposal I attempt to incorporate license and bidder characteristics in the estimation procedure. Haile and Tamer (2003) allow for some level of license differentiation, but their approach relies heavily on the bidder symmetry assumption. Symmetry severely limits the scope of the analysis as bidder differences affect values and could have a significant reflection in the value reordering due to the DE discounts.

Hong and Shum (2003), on the other hand, allow for both license and auction participant heterogeneity. Nevertheless, their technique is based on information dispersed after each bidder's drop-out of the auction. The counterfactual analysis in this paper is based on the reordering of auction participants valuations dependent on the presence of the DE program. Since different value orders lead to differing drop-out sequences, the information revealed in each scenario varies. As a result the estimation results from the sample are not applicable to the counterfactual cases.

Another estimation technique is proposed in the prominent study on frequency allocation efficiency by Fox and Bajari (2013). In their work the authors evaluate different possible market area (MA) splits for the frequency between 1895 MHz and 1910 MHz and 1975 MHz and 1990 MHz. This work suggests that distributing the territory of the U.S. into 4 licenses instead of 487 leads to an allocation efficiency. Their estimation builds on the pair-wise stability of licenses won by different bidders. A significant short-coming of their paper is that they only utilize the winning bids of all auctions, and thus reveal only information about the winners' values. This restricts the analysis to only recovering the top values which is insufficient for the purposes of the current study. As I am interested in the potential reordering of values due to the DE subsidy, the approach applied by Fox and Bajari (2013) would not provide ample information.

Following a thorough examination of the possible advantages and disadvantages of various estimation techniques I pursue a methodology similar to Paarsch (1997). It is a reduced form approach which manages to account for both license and bidder observable characteristics. As such, it provides an appropriate fit for the research questions examined throughout the paper.

As this paper concentrates on the application of a subsidy program, it also belongs to the family of works which includes Athey, Coey and Levin (2013) and Krasnokutskaya and Seim (2011). Both studies demonstrate that a subsidy program is more beneficial in terms of revenue collection than set-aside auctions. However, Krasnokutskaya and Seim (2011) examines the problem in a first-price seal-bid auction setting while Athey, Coey and Levin (2013) analyzes ascending auctions. Furthermore, Athey, Coey and Levin (2013) is among the first to demonstrate empirically that in ascending auctions a subsidy program may result in higher revenue collections when perfectly implemented. The current paper diverges from the established literature by investigating the effects of eligibility manipulations in the subsidy program. So far, the majority of the economic literature takes subsidy implementation for granted, and very little attention is given to possible misuse of the proposed aid programs.

3.3 FCC Auctions and DE Program

The earlier chapters of this dissertation depict a brief history of frequency distribution and define the characteristics of bandwidth licenses. There is a discussion on the distribution of spectrum wavelength and market areas, as well as the Designated Entity program. The potential effects of the subsidy receive additional attention, and an example illustrates the underlying mechanisms which may lead to either higher or lower auction revenues.

The following section of this chapter expands the presentation on spectrum allocation and the subsidy program implemented to support a more competitive market outcome.

First, I describe the auction design along with the underlying intuition for the necessity of each auction aspect. Then, I prove mathematically the claims introduced in section 2.3. The argument there is that a winning bid discount could lead to an increase or a decrease of auction revenues depending on the specific auction setup. I also provide the exact conditions under which FCC revenues would either rise or fall.

3.3.1 Frequency Auctions

The FCC allocates frequency licenses through simultaneous multi-round auctions: all auctions start and end at the same time. Participants place their bids in rounds for any collection of licenses it deems profitable. The main restriction is that any bids placed for a certain license in any round must be larger than the highest bid from the previous round for that license. The only exception is the first round where firms have to bid non-negative amounts.

As auction participants do not observe each other's bids within a round, there is no requirement to outbid the highest bid in the current round. This enables companies to bid as close to their true value as possible. Whenever strict bid increments are implemented a firm may not be able to bid close to its actual value. Suppose a competitor raises the highest bid by the minimum possible amount but this new bid is extremely close to another firm's value. Then, adding the minimum bid increment may result in a bid higher than the second firm's value. That would preclude the company from bidding close to its actual value.

If all companies can improve on their bids simultaneously, theoretically all auction participants should be able to bid as close to their true license values as possible. Consider a firm in the position where the difference between its value and the highest current bid is less than twice the minimum bid increment. Then, it may bid its value instead of increasing the highest bid by the smallest possible amount. As a result, all firms would bid until their highest bid is no further from their value than the minimum bid increment. Furthermore, firms are not restricted in the number of bids they can make within a round, but for each license only their highest bid counts.[1]

The FCC has no fixed maximum number of rounds in which an auction set must conclude. Instead, all auctions are open so long as there is a new bid for at least one license. This auction characteristic allows firms to bid in an auction that has not been active for a number of rounds. Currently, all auction sets have concluded within 300 rounds.

3.3.2 Effect of DE Program on Auction Outcomes

If discounts are applied in a linear pricing setting, the result will always be lower revenues for the supplier. However, in an ascending auction setting the price is a consequence of firm interaction, and depends on the order of participants' values. In his inaugural paper on auctions Vickrey (1961) notes that second-price sealed-bid auctions, which are outcome equivalent to ascending auctions, are won by the company with the highest value. That firm's winning bid is marginally higher than the final bid placed by the firm with the second highest value. Overall, in ascending auctions the firm with the highest value wins the auctions with a bid equal to the value of the company with the second highest value.

The discounts for DEs act as value inflators - qualifying companies can now bid higher amounts, because they will pay less than the placed bids. This rearranges the value ordering for the firms participating in the auction. The consequences of such reordering could be generally classified into 3 possible cases:

1. The DE is not among the firms with the top 2 values

2. The DE becomes the firm with the 2^{nd} highest value

3. The DE becomes or remains the firm with the highest value

The first scenario is trivial to the current analysis as it does not change the auction winner or the amount of the winning bid.

In the second case the firm with the highest value still wins the license because it can still outbid the DE. Thus, there is no change in the identity of the winning firm.

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[1] There are no theoretical incentives for firms to improve on their bids during the same round. Nevertheless, I observe such behavior in the data.

Nevertheless, there is a change in the winning bid. The winner now has to improve not only on the bid of the original second highest value but also on the inflated value of the DE. This guarantees that while the winning firm still secures the license, it is forced to place a larger bid in order to win it.

In the last situation, when the DE has the highest value of all auction participants, it can outbid all other competitors and secure the license. However, the amount it pays for the license is smaller than the original payment that would have been made by the winning firm if there were no subsidies. If the DE was the firm with the highest value even when no subsidies are present, the only difference is that the winning bid becomes discounted. The more intricate case is when the DE becomes the winner due to the discount. Then, the argument for the decrease in the FCC revenues is not obvious. The phenomenon can be observed if we consider a case where the highest two values in the auction are denoted v_1 and v_2. If we let $\tilde{v}$ be the value of the DE before the program was introduced, v^* the value of the DE after the program is implemented, and s the subsidy, then :

$$\tilde{v} = (1 - s)v^* \tag{3.1}$$

The DE does not win the auction without the discount program, so :

$$v_2 \geq \tilde{v} \tag{3.2}$$

However, the DE wins the auction when the program is introduced :

$$v^* > v_1 \tag{3.3}$$

Substituting (3) into (1) yields

$$\tilde{v} > (1 - s)v_1 \tag{3.4}$$

Combining (2) and (4) produces the final result

$$v_2 > (1 - s)v_1 \tag{3.5}$$

The key observation is that the winning bid without the subsidy program would have been v_2 but when the program is introduced it becomes v_1. This is because without the program the firm with value v_1 only needs a bid of v_2 to secure the auction. When the discounts are present, the DE needs to outbid the original winner, which can be achieved by placing a bid of v_1. Nevertheless, the DE does not pay the full amount of v_1 because it qualified for a subsidy of size s. Thus, the DE only pays the commission $(1-s)v_1$, and as per equation (5) that payment is lower than the original payment of v_2.[2]

In summary, the presence of the DE entity discounts could increase the number of licenses held by small firms. However, it is not necessarily clear what the effect of the program is on the revenue collections by the FCC. Because of the opposing effects that may result from the change in value ordering due to the DE discounts, the auction revenues could increase or decrease. That requires an empirical examination of the problem, as there is no concrete theoretical backing for the direction of the revenue change.

3.4 Data

The final sample used for the analysis consists of data from the FCC auction records, as well as county level population characteristics form the census database. The FCC data is formatted according to Yordanov (2015) - the analysis uses the records from auction sets 11, 66, and 97. As the auction sets are held in 1997, 2006, and 2015, I combine this data with population characteristics from 1996, 2005, and 2014. This reflects the earliest estimates of market characteristics firms could have used to determine their bidding strategies.

The FCC auction records supply the bidders' identity and the bids placed by each participant in every auction. The difference between the gross and net bids provides the base for extrapolating whether a firm is granted subsidy status by the commission. The FCC auction records also hold license characteristics such as bandwidth size, location in physical space of the frequency bandwidth, and the MA for which the license is issued.

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[2] A more in depth explanation along with examples can be found in Yordanov (2015).

The merging of license data with population characteristics is based on the counties involved in the license MA. All MAs consist of full counties which eases the data aggregation necessary for matching population and license characteristics. The population characteristics I use in the analysis are race, gender, age, and income characteristics, as well as population size.[3]

A notable characteristic of the current dataset is the split of companies between small and non-small firms. The identification is made on a case by case basis - each auction participant is examined for its connection to a large firm. Of specific interest is whether the firm is a subsidiary of a large company, has a contract with a large firm, or has a contract with a large corporation's subsidiary. If there is no evidence of any of these connections, the firm is marked as a small enterprise. However, if there is evidence of any of the three criteria, the firm is denoted as non-small.

The final dataset consists of 343 unique bidders, 210 of which are small firms. The companies compete in 3 auction sets consisting of a total of 4,110 licenses. The licenses span 15 unique frequencies and 1,389 different MAs. The sample holds records of 18,834 individual bids. The complete summary statistics of the data are presented in Table 3.1. Firms which received the subsidy status placed 42.5% of the bids but only 22.3% of all the bids are placed by true DEs. The discrepancy arises from the fact that 20.1% of the bids are placed by LFAs. This means that half of the subsidized bids belong to firms that should not have qualified for the discount. This could lead to licenses which would have been won by small firms to be secured instead by LFAs. Furthermore, as discussed in section 3.2, this could have an impact on the revenue collections.

3.5 Estimation framework

The bidding strategy of firms involved in the FCC frequency auctions are based on their individual perceptions of the license value. Nevertheless, there is a common component to those valuations - the population size of the market area, the population composition,

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[3] The racial categories are white, black, hispanic, native american/islander, and asian. The excluded racial category is white. The excluded gender category is male. The excluded age category is not-senior.

Table 3.1: Summary statistics

The final sample is a balanced panel dataset containing 18834 observations. Bid amounts are measured in terms of 2015 U.S. dollars

Variable	**Mean**	**Std. Dev.**	Min	Max
Bid Amount	12793.851	78085.243	0.001	2762964
# of bidders	5.385	1.893	1	11
𝟙(Small Firm)	0.279	0.449	0	1
# of DEs	1.248	1.356	0	8
# of LFAs	1.148	1.141	0	4
Fraction DEs	0.225	0.237	0	1
Fraction LFAs	0.201	0.203	0	1
Block Size	11.714	4.105	5	20
Frequency Block Start	1789.065	70.242	1695	1890
𝟙(LFA)	0.201	0.401	0	1
𝟙(DE15)	0.03	0.172	0	1
𝟙(DE25)	0.194	0.395	0	1
𝟙(DE35)	0	0.019	0	1
Black population	15314.964	48623.393	0	847314
Hispanic population	27775.804	120898.426	0	1803547
Native population	1724.841	5622.989	0	109091
Asian population	9480.960	51236.737	0	644228
Female population	75159.621	177743.647	33	2174151
Senior population	27579.216	61169.777	16	742807
Population	148469.757	352816.057	70	4336853
Log(Mean Household Income)	10.549	0.268	9.749753	11.58248
Auction Set	61.058	38.529	11	97

the amount of frequency allotted to the license, etc. These observable characteristics are common knowledge and remain the invariant for all participants. The differences in license valuations for different bidders arise from features unobservable to the researcher. This prompts the use of a parametric model which captures the effect of observable bidder and license attributes.

One prospective functional form for the analysis in this paper is

$$\begin{aligned}\log(\text{Bid}_{it}) = \quad & \alpha + \gamma^C \# \text{ of bidders} + \gamma^{subsidy}\text{Frac subsidy status}_t + \beta X_t + \omega D_t \\ & + \mu_m + \delta_i + \epsilon_{it}\end{aligned} \tag{3.6}$$

In this framework i, t, and m are respectively participant, auction/license, and market area indicators. Frac subsidy status$_t$ measures the fraction of competitors which received discount prior to the start of the frequency auctions. The license characteristics are contained in X_t, while D_t denotes the demographic characteristics. There are two types of fixed effects : μ_m - the market area fixed effects; and δ_i - the participant fixed effects.

The specification depicted in (6) does not reflect the fact that LFAs may also receive the subsidy status. Since firms may react in different ways to true DEs than they would to LFAs which received the status, the two have to be separated. The result is equation (7).

$$\begin{aligned}\log(\text{Bid}_{it}) = \quad & \alpha + \gamma^{C}\#\text{ of bidders} + \gamma^{DE}\text{Frac DEs}_t + \gamma^{LFA}\text{Frac LFAs}_t \\ & + \beta X_t + \omega D_t + \mu_m + \delta_i + \epsilon_{it}\end{aligned} \tag{3.7}$$

The new elements Frac DEs$_t$ and Frac LFAs$_t$ are the fraction of bidders which are respectively true DEs and LFAs.

The model proposed in equation (7) can be further developed. In addition to the distinction between true DEs and LFAs, it is also beneficial to differentiate between small firms and non-small firms as defined in section 3.4. Even though more than 60% of the firms in the sample are small firms, they only account for 27.9% of the bids. That suggests there are significant differences in the license preferences between small firms and other firms. Therefore, it is necessary to distinguish between the responses of small firms and other auction participants.

$$\begin{aligned}\log(\text{Bid}_{it}) = \quad & \alpha + \gamma^{C}\#\text{ of bidders} \\ & + \gamma^{DE}_{SF}\mathbb{1}(SF)_i * \text{Frac DEs}_t + \gamma^{DE}_{NSF}\mathbb{1}(NSF)_i * \text{Frac DEs}_t \\ & + \gamma^{LFA}_{SF}\mathbb{1}(SF)_i * \text{Frac LFAs}_t + \gamma^{LFA}_{NSF}\mathbb{1}(NSF)_i * \text{Frac LFAs}_t \\ & + \beta X_t + \omega D_t + \mu_m + \delta_i + \epsilon_{it}\end{aligned} \tag{3.8}$$

In equation (8) $\mathbb{1}(SF)_i$ is an indicator whether the bidder is a small firm and $\mathbb{1}(NSF)_i$ is an indicator whether the bidder is not a small firm. A firm can only be small or non-small - every participant belongs to one of the classifications, but not both, so $\mathbb{1}(NSF)_i + \mathbb{1}(SF)_i = 1$. Equation (8) is the framework I use in the rest of the chapter, and is the basis for the counterfactual analysis.

There are two notable terms missing from equation (8). Those are a stand-alone small firm indicator $\mathbb{1}(SF)_i$, as well as auction set fixed effects, which double as time fixed effects.[4] The reason is the arising multicollinearity between those terms and variables already included in the regression. The collinearity of the small firm indicator stems from small firms participating only in a single auction set in the sample data. As a result all companies designated as small entities keep this classification throughout the full sample period.[5] Thus, there is not enough variation in the data which would enable the identification of a small firm indicator coefficient.

The auction set fixed effects, on the other hand, are perfectly correlated with a set of license characteristics - the spectrum block dummies. Each spectrum bandwidth covered by spectrum licenses is only available during the auction set in which it is offered. Consequently, the collection of frequency fixed effects for the bandwidth auctioned in a specific auction set would be equivalent to the single dummy representing the auction set itself. Moreover, since each auction set is only present in a single time period, frequency indicators also eliminate the need for time fixed effects. For that reason, the presence of license characteristics prevents not only the use of auction set controls but also of time-period controls.

3.6 Results

3.6.1 Parametric Estimates

The coefficient estimates from the parametric model depicted in equation (8) are summarized in Table 3.2. Specification (1) includes a competition measurement variable along with a small firm indicator and the interaction terms between the small firm indicator and the fractions of DEs and LFAs. In the presence of these independent variables alone the model explains 12.55% of the bid variation. The explanatory power of the model increases

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[4] Since each auction set is conducted in a different year, the auction set fixed effects are equivalent to time fixed effects.

[5] When analysing the elimination of the subsidy program, I make prediction about the bids of companies which are stripped of their small firm status. Because I do not observe companies changing their status from small to non-small firm in the sample data, such counterfactual predictions are out-of-sample.

Table 3.2: Fixed Effects

The different specification depict the additive explanatory power of fixed effects. DE2 specifies that the DE interactions terms are for the individual subsidy size.

Variable	(1)	(2)	(3)	(4)
Constant	10.4674***	13.4685***	8.2898***	22.0285***
	(0.0971)	(2.3768)	(2.2977)	(6.2797)
ln(# of bidders)	1.5970***	0.3155***	0.2604***	-0.1400***
	(0.0594)	(0.0108)	(0.0112)	(0.0123)
$\mathbb{1}$\{Small firm\} * Frac DEs	0.8984***	-3.5364***	-2.1829***	-1.0609***
	(0.1517)	(0.2545)	(0.2559)	(0.2104)
$\mathbb{1}$\{Small firm\} * Frac LFAs	3.6238***	-1.2660***	0.3280	0.1821
	(0.2477)	(0.3090)	(0.3109)	(0.2570)
$\mathbb{1}$\{Not Small firm\} * Frac DEs	-1.1786***	-4.0717***	-2.2025***	0.4431***
	(0.1521)	(0.1602)	(0.1695)	(0.1554)
$\mathbb{1}$\{Not Small firm\} * Frac LFAs	2.0850***	-2.2866***	-.6580***	0.0562
	(0.1289)	(0.1813)	(0.2075)	(0.1852)
Participant Characteristics	N	Y	Y	Y
License Characteristics	N	N	Y	Y
MA Characteristics	N	N	N	Y
Obs	18834	18834	18834	18834
R^2	0.1258	0.4968	0.5344	0.7696
Adj R^2	0.1255	0.4873	0.5252	0.7460
Root MSE	3.1012	2.3746	2.2852	1.6715

*** Significant at the 1 percent level
** Significant at the 5 percent level
* Significant at the 10 percent level

further to 74.60% if I include bidder, license, and MA characteristics. Since specification (4) provides the best fit to the data, it is the one I use throughout the rest of my analysis.

The coefficient estimates presented in Table 3.2 mostly support economic intuition - small firms with limited financial resources tend to bid lower amounts than the rest of the auction participants. On the other hand, there is no direct explanation for the sign on the competitiveness measure - when there are more competitors in the market the bidding should be more aggressive. The raw data supports this hypothesis as there is a positive correlation between the winning bids and the number of bidders. A possible explanation of this phenomenon is that in auctions with more bidders there are also a lot of low drop out prices. Participants who are discouraged from further bidding do not pursue the license and as a result the average bid decreases.

The reaction to the presence of DEs and LFAs provides an insight into the interaction

Table 3.3: Variable Explanatory Power

The different specification depict the additive explanatory power of fixed effects. DE2 specifies that the DE interactions terms are for the individual subsidy size.

Variable	(1)	(2)	(3)	(4)
Constant	15.4447***	17.2501***	22.4055***	23.0692***
	(6.2202)	(6.2084)	(6.2802)	(6.2856)
ln(# of bidders)		-0.4894***	-0.4894***	-0.5718***
		(0.0534)	(0.0534)	(0.0562)
$\mathbb{1}\{\text{Small firm}\}$ * Frac DEs				-1.1134***
				(0.2105)
$\mathbb{1}\{\text{Small firm}\}$ * Frac LFAs				0.1436
				(0.2572)
$\mathbb{1}\{\text{Not Small firm}\}$ * Frac DEs				0.4238***
				(0.1564)
$\mathbb{1}\{\text{Not Small firm}\}$ * Frac LFAs				0.0654
				(0.1857)
DE status effects	Y	Y	Y	Y
License controls	Y	Y	Y	Y
Demographic controls	Y	Y	Y	Y
Participant effects	Y	Y	Y	Y
Auction Set effects	Y	Y	Y	Y
Market Area effects	Y	Y	Y	Y
Obs	18834	18834	18834	18834
R^2	0.7673	0.7685	0.7685	0.7692
Adj R^2	0.7435	0.7448	0.7448	0.7456
Root MSE	1.6794	1.6754	1.6754	1.6728

*** Significant at the 1 percent level
** Significant at the 5 percent level
* Significant at the 10 percent level

between different types of auction participants as well as the value ordering in the auctions. As predicted most of the coefficients have a positive sign suggesting that discount recipients facilitate higher bids and potentially higher equilibrium prices for the licenses. The only exception to this rule is the reaction of small firms to the presence of DEs. There are two possible explanations for this occurrence. Either small firms drop prematurely from the auction, or they reallocate their resources to other auctions where they may be more successful in securing frequency. The second case, however, would violate the assumption crucial for the counterfactual analysis. Thus, instead of making a claim for a general equilibrium model as in Benkard, Bodoh-Creed, and Lazarev (2010), my predictions only hold when considering each auction as an independent event.

The reaction of non-small firms to DEs is significantly positive - evidence of DEs pushing auction winners into placing higher bids to secure their licenses. This results in higher equilibrium price, and is consistent with the situation where the subsidized entity's inflated value rises in the value order to become the second highest. Then, there is no change in the winning company, but the winner is forced to outbid the new, higher second highest value, thus bidding a higher amount than it would without the DE program.

The positive but statistically insignificant effect of presence of LFAs indicates that LFAs do not have much effect on other companies' bids. This could be because the LFAs' values are not among the top 2 values - a hypothesis not supported by the raw data. Thus, it is more probable that companies are bidding close to their actual values and there is not much room for further increase in their bids when LFAs are present. This would support the argument that LFAs on average win the auctions in which they participate. Despite other companies bidding as high as possible, no firm can outbid a subsidized LFA. If this is the case, when discount eligibility is manipulated it leads to changes in the auction winners and, as discussed in section 3.3.2, to a decrease in the FCC revenue collections.

3.6.2 Policy Analysis

The coefficient estimates indicate that both of the revenue increasing and revenue decreasing scenarios described earlier in this paper are present in the data. This makes the analysis of the subsidy program a non-trivial pursuit and requires the use of counterfactual analysis. The cases of specific interest are when the DE program is not implemented at all, and when the subsidy is introduced, but all eligibility manipulations are eliminated. The first scenario allows me to evaluate the effect the program in its current form including the access manipulation by LFAs. The second counterfactual provides insight into the potential outcome of the program if there is no discount access manipulation. Through this counterfactual I can examine the results of a perfect implementation, as well as create a juxtaposition for studying the effect of LFA's eligibility manipulations.

The evaluations of the DE program and the effect of eligibility manipulations are based on simulations where the DE subsidy or LFA access to the discounts never existed. The simulations are the result of predicting auction participants' bids using the estimated coefficients from equation (8). In order to produce the predictions I assume that all firms maintain their bidding strategy based on observable characteristics regardless of whether they are a DE or a LFA. This is the equivalent to the main assumption utilized by Benkard, Bodoh-Creed and Lazarev (2010). The primary difference is that BBCL examines a merger scenario, whereas I apply their methodology in studying auction bidding.

To construct a world where the DE program is not present, I nullify all DE and LFA statuses. Furthermore, I set the fraction of competitors who are DEs or LFAs in all auction to equal 0. Thus, if firms do not change their bidding behavior based on observable characteristics, the predicted bids will reflect a paradigm where the discounts are never provided to any single company. Similarly, to simulate a state of the world where there are no eligibility manipulations, I change all LFA statuses, as well as the fraction of competitors who are LFAs to 0. This would change the bids to reflect the fact that no LFAs are present in the market anymore.

It is necessary to note that this assumption is relatively strong. Suppose that the estimation coefficients suggest that the presence of DEs or LFAs affects a firm's behavior, not only in the current auction, but also in other auctions. This would be the case if the presence of DEs and LFAs forces some firms to reallocate their resources. Companies may abandon the auctions in which they are involved in favor of others where there is less aggressive bidding because of the presence of fewer DEs or LFAs. In this hypothetical scenario, the assumption would be violated as the presence of DEs and LFAs in other auctions may alter companies' bidding functions for the same set of observable characteristics. This entails that the coefficient estimates have to provide evidence that firms' bidding strategies are independent of the presence of DEs or LFAs in other auctions.

The results of this analysis are presented in Table 3.4. When the DE program is eliminated altogether, the number of licenses won by small firms decrease by 43% from 623 to 357. However, the FCC gains close to 6% in revenues when the subsidy is removed - an increase from \$30.21 billion to \$31.89 billion. These numbers support the claim that the program is a burden on the tax-payers and should be abandoned in order to prevent further harm due to LFA manipulations.

Table 3.4: DE Program Analysis

The revenues are reported in billions of USD.

	# of licenses held by small firms	Auction Revenues
DE implemented as is	623	\$30.21
No DE program	357	\$31.89
No LFA	942	\$34.17

An examination of a perfect program implementation provides a contrasting picture. If all eligibility manipulations are prevented, the number of small firm licenses would increase by 51% from 623 to 942. In addition to this, the FCC revenues would increase by 13% from \$30.21 billion to \$34.17 billion. In a direct comparison between the counterfactuals where the program is not present and where it is perfectly implemented there is a 164% increase in the number of licenses secured by small firms. It would also bring a raise in revenue collections of over 7%.

The analysis suggests that a comparison of the current world to one where the program is eliminated only highlights the shortcomings of the current implementation of the program. Nevertheless, a thorough examination of the program suggests the DE subsidy would not be a failed policy. If the FCC continues its efforts to eradicate the discount access manipulations by LFAs, the revenue losses can be eliminated. In a setup where only the true DEs have access to the program, not only would small firms greatly benefit form reallocated licenses, but the FCC would also benefit financially. Improving the access control for the program could eliminate the trade-off between policy provision and loss of auction receipts.

3.7 Model Limitations

The results of this chapter highlight the importance of methodology choice when performing counterfactual analysis. There are notable differences in the size and direction of the effects from subsidy access restrictions, as well as the program's abolition. Notably, there is also difference in the simulated equilibrium bids and auction revenues for the current state of the world - the benchmark for comparison against counterfactual results.

The disparity stems from the fact that the estimated value distributions in chapter 2 are based on the observed bid distribution. Because the functional form in chapter 3 imposes strict distributional assumptions it does not fit the data as well as the non-parametric approach. Thus, the equilibrium bids in the current state of the world are better approximated by the simulations using value distributions rather than the restrictive functional form. This is the main shortcoming of the reduced form methodology.

As discussed earlier the motivation for applying a parametric framework is based on the necessity to account for bidder heterogeneity. The ability of the analysis in this chapter to better account for equilibrium bid variation stemming from bidder characteristics increases the credibility of the counterfactual results. The intuition for the introduction of the DE program relies on the inherent variation in bidder's financial constraints, so it would be illogical to assume all firms are subject to the same value distribution. The reduced form approach provides for a more adequate differentiation of the value distributions, and respectively equilibrium bids. This improves the reliability of the evaluation of the effect of subsidy access restrictions. While the absolute magnitude of the effects likely differs by an order of magnitude, the relative effect measured in percentage terms should not be affected.

Chapter 4

Overview and Policy Implications

Since the beginning of 2015 the FCC has been heavily criticized for the loopholes in the eligibility criteria for its DE program and the resultant competitive edge for LFAs. Pundits have requested that the discounts be scrapped and the FCC refrains from altering future auction outcomes. Nevertheless, as this dissertation advocates, such course of action may not be fully justified. Critics of the policy consider it strictly as a money transfer and ignore the interactive nature of auctions. As demonstrated in the literature, the effect of discounts is non-trivial in ascending auctions such as those used by the FCC. Firm subsidies may decrease license acquisition costs or facilitate higher equilibrium prices.

This dissertation examines the DE program applying two different methodologies. One approximates the value distribution of auction participants, and the other estimates equilibrium bids as a function of firm and auction characteristics. Both frameworks provide evidence that restricting discount access to truly small firms would lead to these companies winning more spectrum licenses. Furthermore, eliminating the program altogether would grant more bandwidth to large firms, and threaten a potential evolution of the telecommunication markets into oligopolies. If the FCC's target is a more competitive industry environment, restricting access to the the DE program would be more beneficial than abolishing the discounts.

The effect of the program on auction revenues is more ambiguous, and varies based on the applied methodology. In the case of the nonparametric approximation of auction participant value distribution, the auction collections decrease though the change is statistically insignificant. Effectively, when the FCC provides the subsidy in its current form, its revenues not only do not decrease, but they even slight rise. If the commission decides to impose stricter criteria for firms to qualify for the discounts, the program would come at little to no expense.

These findings are contrasting with the results from the reduced form estimation. When applying a parametric framework there is a cost for the commission to provide the DE program in its current form. Nevertheless, when access to the winning bid discounts is limited to only truly small firms, profits increase enough to offset the initial loss of revenue. My findings suggest that the tightening of eligibility criteria may even drive an increase in auction revenues as high as 10%.

These two frameworks reflect the two extremes in terms of modelling the FCC frequency license auctions. The nonparametric methodology allows the data to dictate the value distributions, and as such provides a good fit to the auction results observed in the real world. However, this model provides limited ability to differentiate between value distributions of individual auction participants. The reduced form approach imposes a restrictive functional form which worsens the data fit, but accounts for crucial bidder heterogeneity.

The juxtaposition of these methodologies provides a range in which the true effects of restricting or eliminating the DE program lie. Therefore, at worst eliminating or restricting access to the subsidy would lead to a small loss of revenue. At best - there would be an increase in the auction collections, with a much larger fund influx when the subsidy eligibility is restricted. It is likely that there are benefits for the FCC to reap from restructuring the discount qualification criteria. There would be gains not only in the financial contributions of the auctions, but also higher chances of a long-run competitive environment in the telecommunication industry.

These potential advantages have strong policy implications. Instead of surrendering to populist calls for less government intervention, the commission can gain from concentrating on effectively implementing its current regulations. There is no need for complete overhaul of the current legislation - just slight modification such as eradication of the perverse incentives for LFAs to manipulate their access to the program. Once this goal is achieved the DE program has the potential to perform as intended and benefit both small firms, and the commission's auction revenues.

Appendix

A Auctions

Spectrum licenses are issued for a certain strip of frequency bandwidth over a specified geographic area. The granted spectrum is distributed according to one of several bandwidth standards. The standards employed by this paper are Personal Communication Services(PCS) which refers to the bandwidth from 1850 MHz to 1990 MHz, and Advanced Wireless Services which covers the range between 1710 MHz and 2180 MHz range.

Additionally, each standard is split into several blocks - each with a size of 5, 10, 15, 20, or 30MHz. The standards are divided into the following blocks:

- Broadband PCS - Blocks A (30MHz), B (30MHz), C (30MHz), D (10MHz), E (10MHz), and F (10MHz)
- AWS-1 - Block A (20MHz), B (20MHz), C (10MHz)[1], D (10MHz), E (10MHz), and F (20MHz)
- AWS-3 - Block A1 (5MHZ), B1 (10MHz), G (10MHz), H (10MHz), I (10MHz), and J (20MHz)

The frequency blocks are non-overlapping, and unless a company holds a license to a certain frequency, it cannot transmit a signal at that frequency. That warrants that the signal of the license holder is not interrupted by other parties attempting transmission at

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[1] In certain market areas due to the high demand for frequency, the FCC split the 30MHz block C into 2 15MHz blocks - C1 and C2, or into 3 10MHz blocks - C3, C4 and C5

Table 1: Mobile Telecommunication Spectrum Auction Sets

Auction Set	Frequency Blocks Offered
4	Broadband PCS, Block A & B
5	Broadband PCS, Block C
10	Broadband PCS, Block C
11	Broadband PCS, Block D, E, & F
22	Broadband PCS, Block C, D, E, & F
35	Broadband PCS, Block C & F
45	Cellular rural service areas
58	Broadband PCS, all blocks
66	AWS-1, all blocks
71	Broadband PCS, all blocks
77	Closed Cellular Unserved
78	Broadband PCS and AWS-1, all blocks
97	AWS-3

the same frequency.

When auctioning telecommunications frequency license, the FCC breaks down the territory of the United States according to one of five possible geographic licenses schemes: Basic Trading Areas (BTAs); Major Trading Areas (MTAs); Cellular Market Areas (CMAs); Basic Economic Areas (BEAs); and Regional Economic Areas (REAs). For any of the geographical schemes, every market area consists of whole counties. That means that every county within the borders of the U.S. is contained in one and only one market area. As any frequency block is auctioned for only a single type of geographic scheme, the market area design guarantees that no two licenses for the same spectrum strip overlap geographically.

Additional information on the frequency blocks physical location and the geographic schemes is available on the FCC wireless auction web-site.[2] The commission records contain graphs presenting the positioning of frequency blocks with respect to one another, as well as maps depicting the geographic schemes.

Licenses for frequency are distributed through auction sets, identified by their sequence number. The auction set utilized in this study are those pertaining to mobile telecommunications. They are displayed in Table 3.6 along with the exact frequency blocks offered for auctioning. The DE program is first introduced in auction 5, and has

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[2] `http://wireless.fcc.gov/auctions/default.htm?job=auctions_data`

been present in every auction set since then.

B Ordered Statistics

Haile and Tamer (2003) base their approach on the fact that even when all values for an auction are drawn from a single distribution, splitting bids depending on their auction rankings results in the bids behaving as though they are drawn from different distributions. The distribution for all bids which ranked first, would be different from the distribution of all bids which ranked second. Those two distributions would be different from the distribution of all bids which ranked third, and so on. These ordered statistics are particularly useful as there is a very strict relationship between the ranked bid distributions and the parent distribution from which all bids are drawn. In particular,

$$F_{i:n}(v) = \sum_{r=i}^{n} \binom{n}{r} F(v)^r (1 - F(v))^{n-r} \tag{1}$$

where $F_{i:n}(v)$ is the CDF of the distribution of the i^{th} lowest value out of n participants in an auction, and $F(v)$ is the parent CDF of the distribution from which all values are drawn. Equation (12) depicts the discrete case, while

$$F_{i:N}(v) = \frac{N!}{(N-i)!(i-1)!} \int_0^{\phi} s^{i-1}(1-s)^{N-i}\, ds \tag{2}$$

represent the continuous formulation where s is the variable of integration.

The formula in equation 12 states that for a value v to be the i^{th} lowest in an auction, then at least i values must be as low as v, and all other bids have to be larger than it. Hence, we find the probability that r participants have values of no more than v, and the other $n - r$ have values higher than it. The key is that r has to be at least i, but can go as far as n, since all that is required is for v to be the i^{th} highest value. However, there are no other restrictions to the values of the other auction participants and there could be multiple companies with the value of v. Since the definition doesn't explicitly state which of the n auction participants have realizations smaller or equal to v, the formula takes into account for all possible combinations.

Exploiting that relationship between order statistics distribution and parent distribution for the differently ranked bidders Haile and Tamer (2003) manage to convert the inequalities between ordered bids and ordered values into bounds for the value distribution. The first bidding behavior assumption guarantees an upper bound, and the second assumption provides a lower bound.

C Binary Search

Solving for the implicit solution of the ordered statistic formula is a non-trivial task. I utilize the monotonicity of the distribution transformation to apply the binary search algorithm. In this particular case I search for the implicit solution among a selected set of points. For any element of that set I evaluate the integration ordered statistic formula (equation 13) and compare it to the ordered statistic CDF value.

The algorithm requires the use of continuous domain. The set of values is initially set to the full domain. Then, I evaluate the function at the searching set midpoint. If the midpoint evaluation is larger than the ordered statistics CDF value, I restrict the searching set to its first half. Otherwise, I restrict the set to its second half.

The refinement of the search set at each iteration shrinks the set of values which contain the implicit solution. As the interval is continuous, and the searching set can be halved for infinitely many iterations, I set a tolerance level of 10^{-6}. Once the length of the searching set is smaller than the tolerance level I stop the procedure, and take the interval midpoint as the solution.

As an example, let the domain be the value between 0 and 3, and search for the implicit solution of the increasing continuous function $f(x) = x^2$. Analytically, we know that the solution of $f^{-1}(4) = 2$. I can also use the binary search algorithm to find the implicit solution for $f(x) = 4$. The starting point is to set the searching set as the interval [0, 3]. Then, I evaluate $f(x)$ at the midpoint - 1.5.

$$f(1.5) = 2.25$$

Since $2.25 < 4$, the implicit solution to the problem cannot be smaller than 1.5 due to monotonicity. Thus, it has to be the case that the true solution is in [1.5,3].

The second step of the algorithm requires that I redefine the searching set as [1.5,3]. Then, I find the midpoint and re-evaluate the function $f(x)$. The result is

$$f(2.25) = 5.0625$$

Since $5.0625 > 4$, the implicit solution to the problem cannot be bigger than 2.25 due to monotonicity. Thus, it has to be the case that the true solution is in [1.5,2.25].

Once I have established the new search set, I continue evaluating at the midpoint and restricting the possible set of values which contain the solution. After a finite number of steps this approach yields an interval around 2 with a width of at most 10^{-6}.

D Boundary Smoothing

Section 2.6.1 discusses the possibility for the upper and the lower bounds to intersect. The reason for the problem with empirically applying the theoretical bounds is the convexity of the maximum function and the concavity of the minimum function. To overcome that obstacle, Haile and Tamer (2003) recommend using a weighted average function. The specific functional form proposed by the authors is

$$\mu(\hat{y}_1, \hat{y}_2, ..., \hat{y}_J; \rho) = \sum_{j=1}^{J} \hat{y}_j \left[\frac{\exp(\hat{y}_j \rho)}{\sum_{j=1}^{J} \exp(\hat{y}_j \rho)} \right] \tag{3}$$

where $\hat{y}_j \in [0, 1]$. The appeal of this weighted average stems from the fact that through changes in the parameter ρ, the researcher can alter the behavior of the function.

$$\rho \to +\infty \Rightarrow \mu(\hat{y}_1, \hat{y}_2, ..., \hat{y}_J; \rho) = \max(\hat{y}_1, \hat{y}_2, ..., \hat{y}_J) \tag{4}$$

$$\rho \to -\infty \Rightarrow \mu(\hat{y}_1, \hat{y}_2, ..., \hat{y}_J; \rho) = \min(\hat{y}_1, \hat{y}_2, ..., \hat{y}_J) \tag{5}$$

Haile and Tamer (2003) prove the validity of equations (14) and (15). Furthermore, the authors suggest that a substitution of ρ with a random large positive (negative) number approximate the maximum (minimum) function. Applying the smoothing approach alleviates significantly the problem of intersecting upper and lower bounds for the firm values CDF.

E Additional Tables and Figures

Table 2: Placed bids by type of subsidy allocation

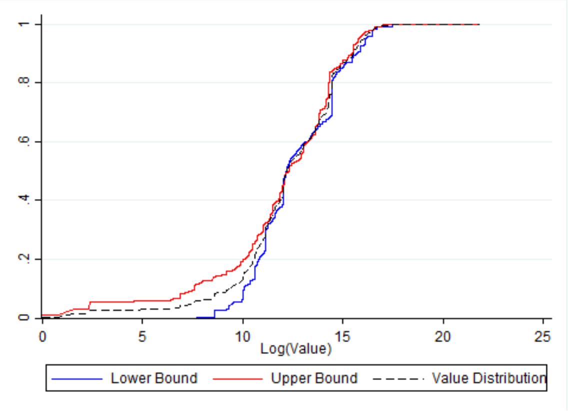
The table summarizes the bids measured in '000s of U.S. dollars. All sections contain information on license auctions with at least 2 bidders in FCC auction 11, 66, and 97. Part I presents the data from auction 11, part II - from auction 66, and part III - from auction 97. Section A contains statistics on the highest bids placed by a company an auctions. Section B contains statistics on just the winning bids, and section C contains the information on the non-winning bids.

Variable	Obs	Mean	St. Dev.	Min	Max
I. Auction 11					
A. All Bids					
Total	6,612	1,135.23	4,107.20	0.00	100,320.00
No subsidy	4,708	1,168.99	3,927.69	0.00	62,741.00
15% subsidy	262	343.72	806.40	0.10	7,041.89
25% subsidy	1,635	1,169.69	4,857.69	0.01	100,320.00
35% subsidy	7	0.01	0.00	0.00	0.01
B. Winning Bids					
Total	1,455	1,800.67	5,650.30	2.01	100,320.00
No subsidy	1,006	1,803.80	5,351.98	2.01	62,741.00
15% subsidy	74	616.84	1,131.55	9.90	5,481.33
25% subsidy	375	2,025.89	6,824.22	9.80	100,320.00
35% subsidy	0	-	-	-	-
C. Non-Winning Bids					
Total	5,157	947.48	3,530.74	0.00	91,200.01
No subsidy	3,702	996.49	3,420.91	0.00	57,037.00
15% subsidy	188	236.22	605.51	0.10	7,041.89
25% subsidy	1,260	914.86	4,063.03	0.01	91,200.01
35% subsidy	7	0.01	0.00	0.00	0.01

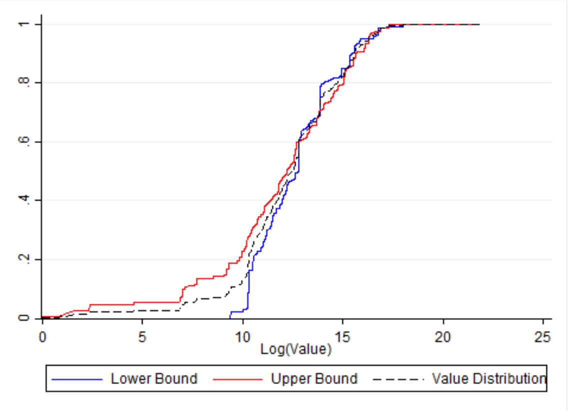
cont.

II. Auction 66					
A. All Bids					
Total	3,328	15,698.40	64,289.12	8.10	1,335,374.00
No subsidy	2,364	19,506.10	73,410.42	8.10	1,335,374.00
15% subsidy	225	1,169.12	2,696.63	11.00	25,546.00
25% subsidy	739	7,941.53	34,697.82	19.00	421,511.00
35% subsidy	0	-	-	-	-
B. Winning Bids					
Total	924	14,988.38	77,359.43	11.00	1,335,374.00
No subsidy	751	17,475.21	84,491.85	12.00	1,335,374.00
15% subsidy	68	590.97	680.38	11.00	3,006.00
25% subsidy	105	6,525.70	37,110.94	29.00	365,445.00
35% subsidy	0	-	-	-	-
C. Non-Winning Bids					
Total	2,404	15,971.30	58,509.98	8.1	1,112,812.00
No subsidy	1,613	20,451.67	67,642.53	8.10	1,112,812.00
15% subsidy	157	1,419.52	3,167.64	11.00	25,546.00
25% subsidy	634	8,176.01	34,307.19	19.00	421,511.00
35% subsidy	0	-	-	-	-
III. Auction 97					
A. All Bids					
Total	8,739	20,733.59	106,691.70	1.00	2,762,964.00
No subsidy	3,630	26,513.12	119,177.90	1.00	2,762,964.00
15% subsidy	77	1,080.61	1,398.28	49.00	9,680.00
25% subsidy	5,032	16,865.06	97,366.57	2.10	2,712,964.00
35% subsidy	0	-	-	-	-
B. Winning Bids					
Total	1,576	28,238.90	130,709.60	8.40	2,762,964.00
No subsidy	636	47,605.19	178,131.80	9.60	2,762,964.00
15% subsidy	10	682.90	543.14	185.00	1,965.00
25% subsidy	930	15,291.16	82,726.06	8.40	1,315,700.00
35% subsidy	0	-	-	-	-
C. Non-Winning Bids					
Total	7,163	19,082.27	100,576.70	1.00	2,712,964.00
No subsidy	2,994	22,032.64	101,856.90	1.00	2,362,964.00
15% subsidy	67	1,139.97	1,477.73	49.00	9,680.00
25% subsidy	4,102	17,221.89	100,395.00	2.10	2,712,964.00
35% subsidy	0	-	-	-	-

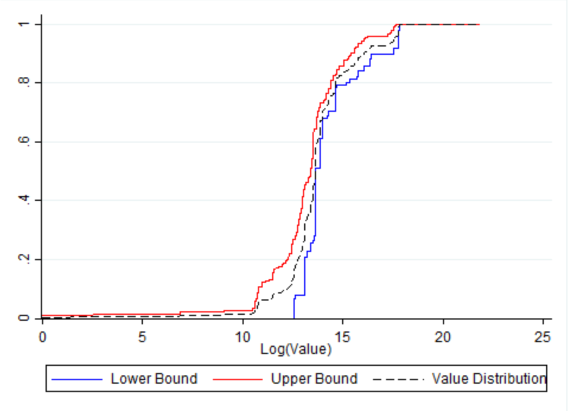
Figure -1: Market-Size Estimation Results, PCS Block D



(a) Small Market

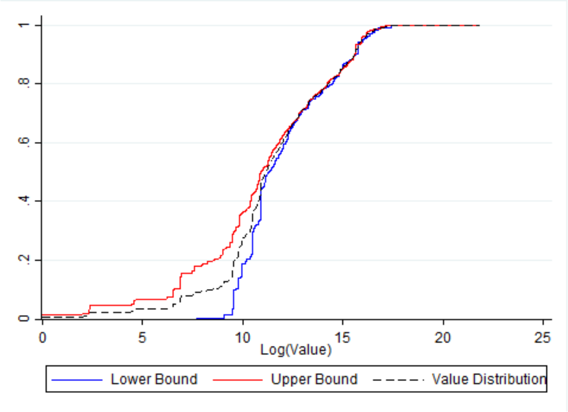


(b) Medium Market

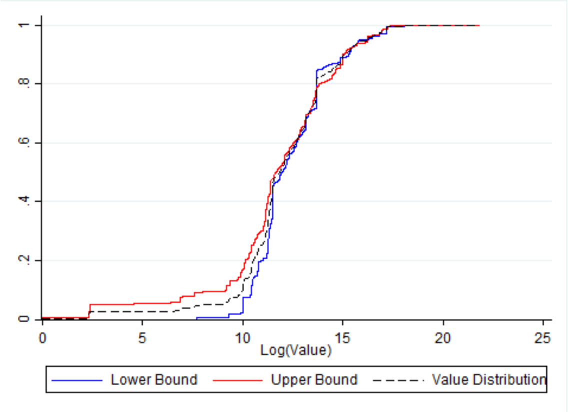


(c) Large Market

Figure -2: Market-Size Estimation Results, PCS Block E



(a) Small Market



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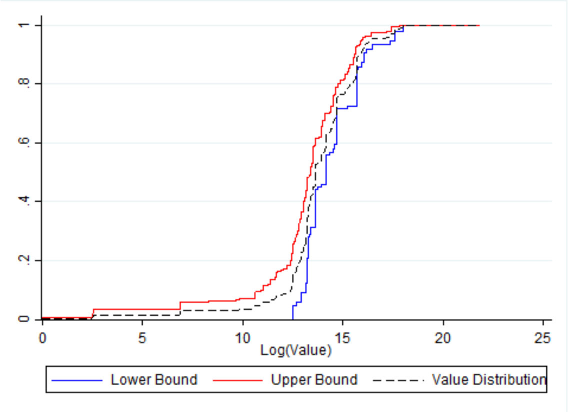
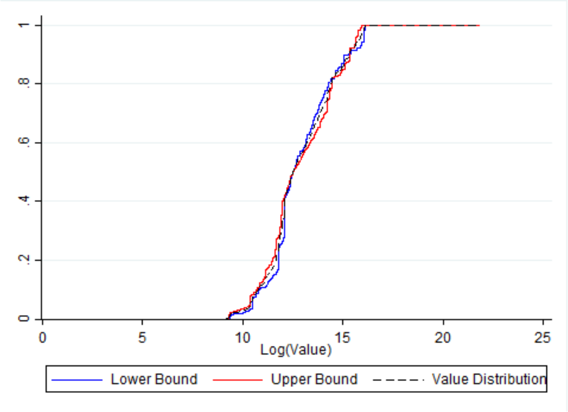
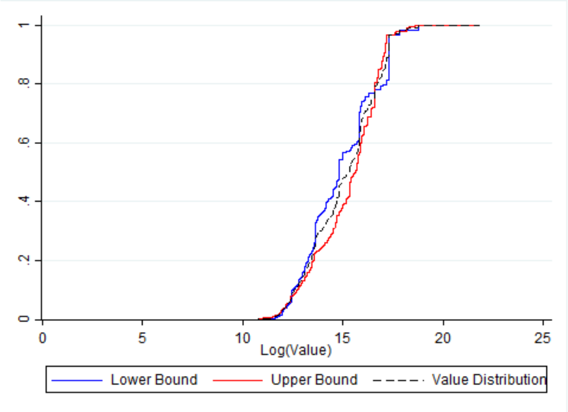


(c) Large Market

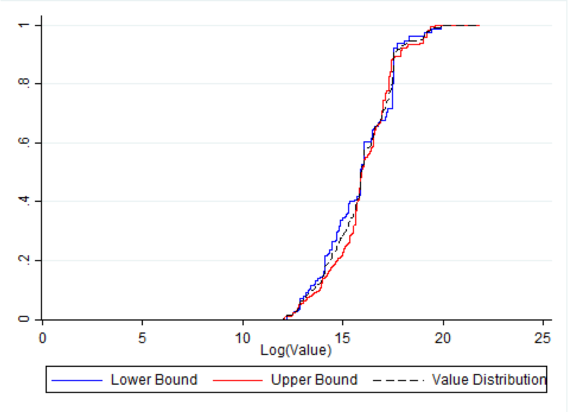
Figure -3: Market-Size Estimation Results, AWS-1 Block A



(a) Small Market

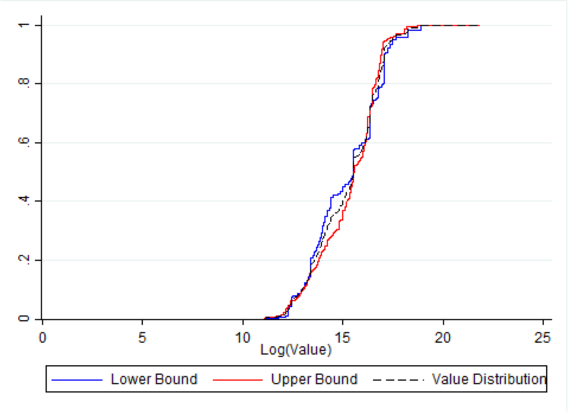


(b) Medium Market

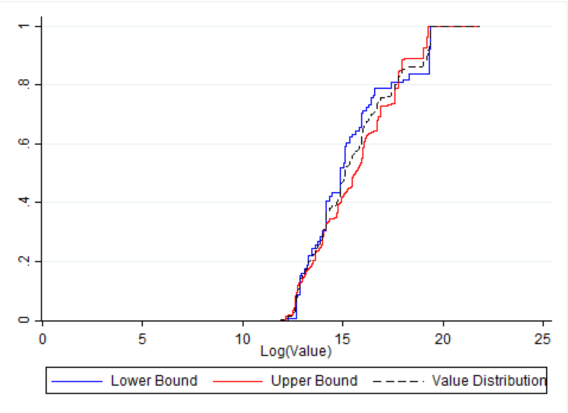


(c) Large Market

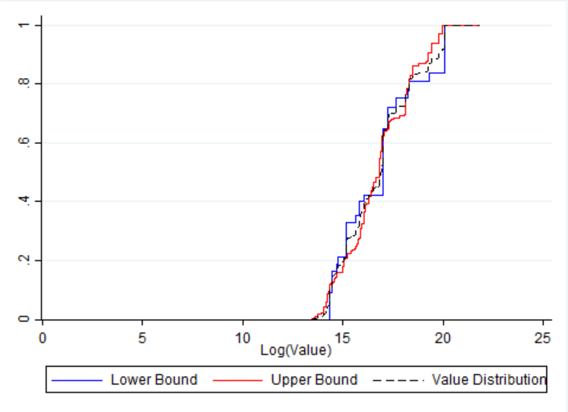
Figure -4: Market-Size Estimation Results, AWS-1 Block B



(a) Small Market

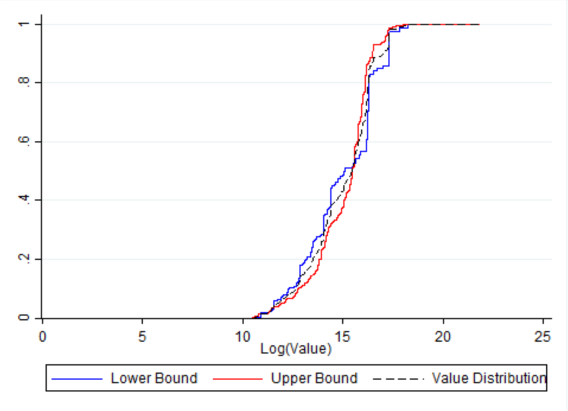


(b) Medium Market

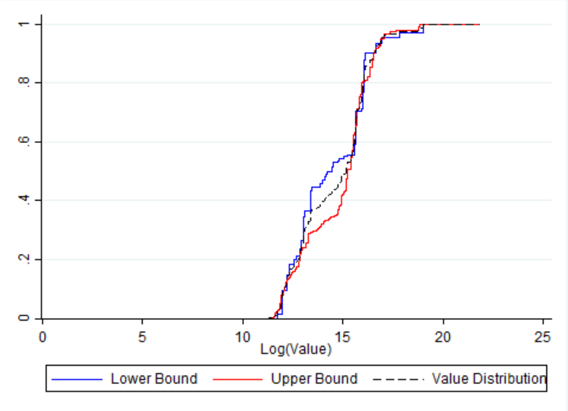


(c) Large Market

Figure -5: Market-Size Estimation Results, AWS-1 Block C



(a) Small Market



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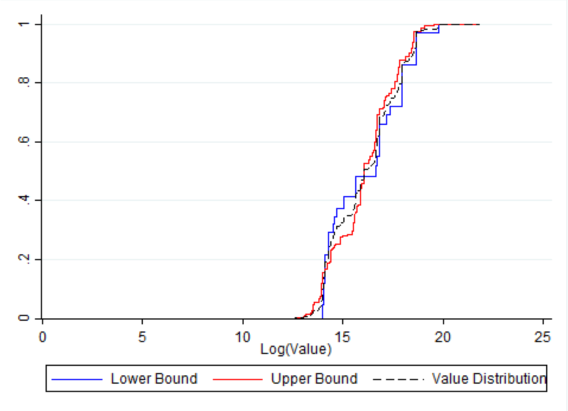
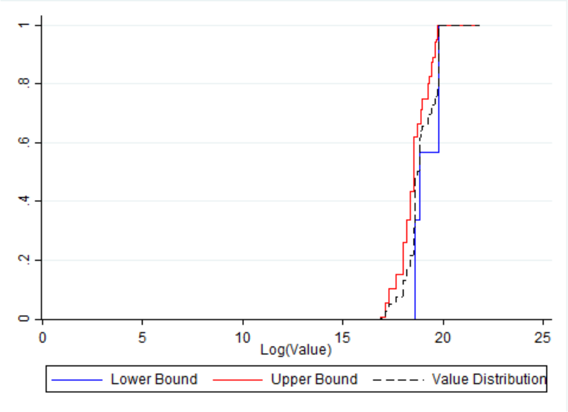
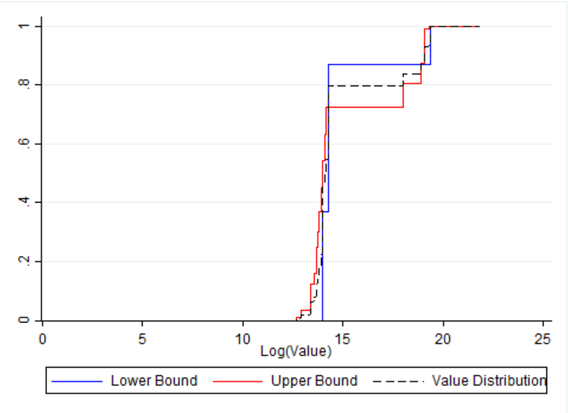


(c) Large Market

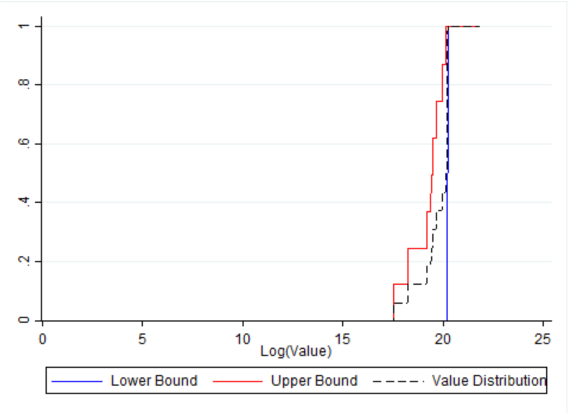
Figure -6: Market-Size Estimation Results, AWS-1 Block D



(a) Small Market

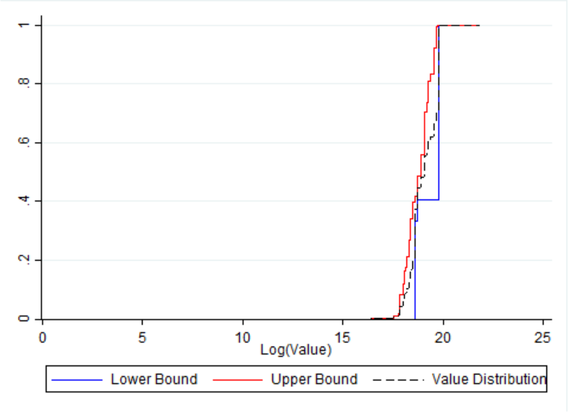


(b) Medium Market

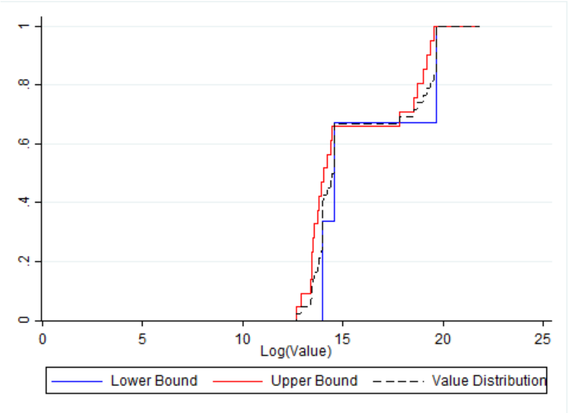


(c) Large Market

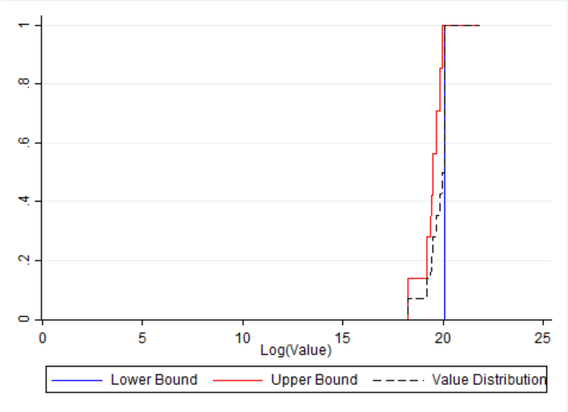
Figure -7: Market-Size Estimation Results, AWS-1 Block E



(a) Small Market

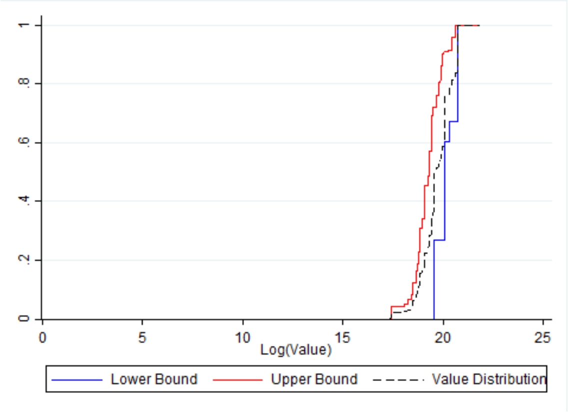


(b) Medium Market

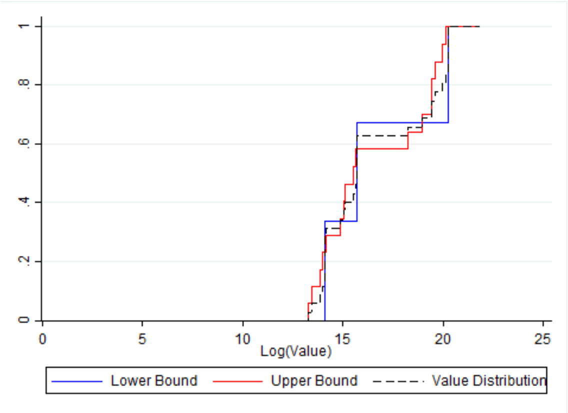


(c) Large Market

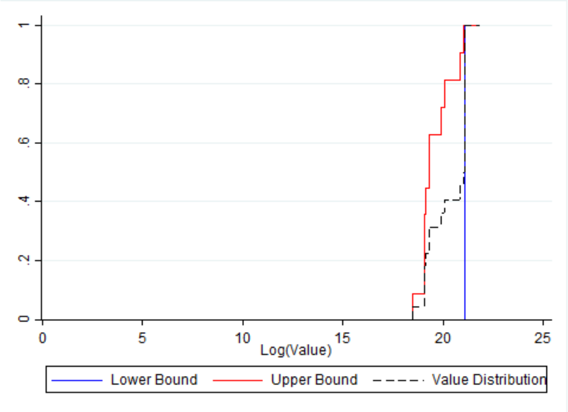
Figure -8: Market-Size Estimation Results, AWS-1 Block F



(a) Small Market

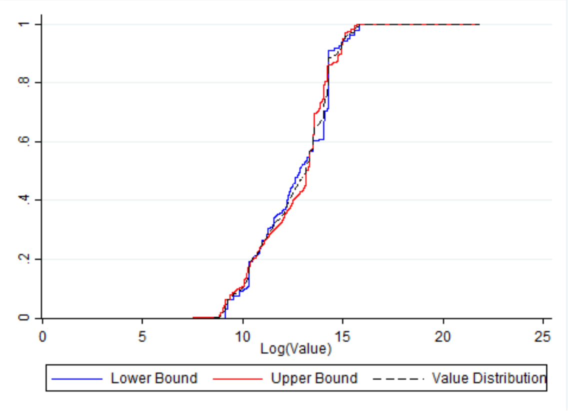


(b) Medium Market

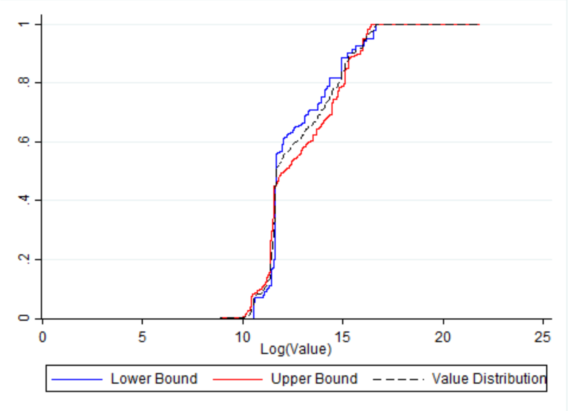


(c) Large Market

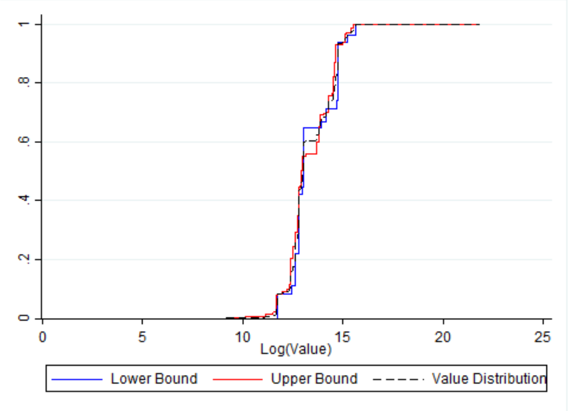
Figure -9: Market-Size Estimation Results, AWS-3 Block A1



(a) Small Market

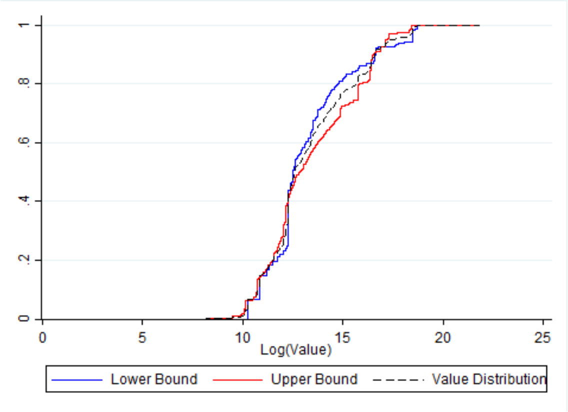


(b) Medium Market

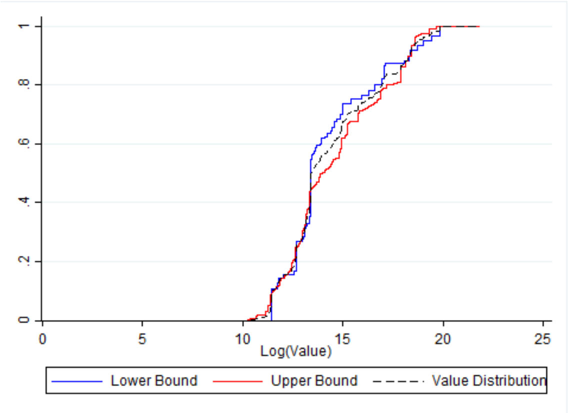


(c) Large Market

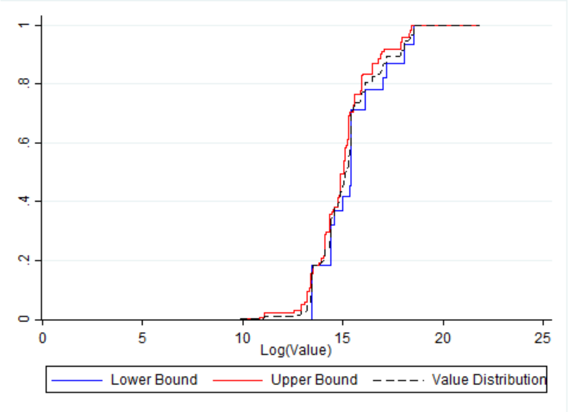
Figure -10: Market-Size Estimation Results, AWS-3 Block B1



(a) Small Market

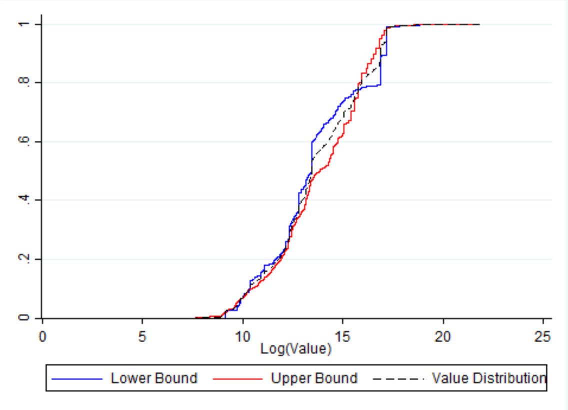


(b) Medium Market

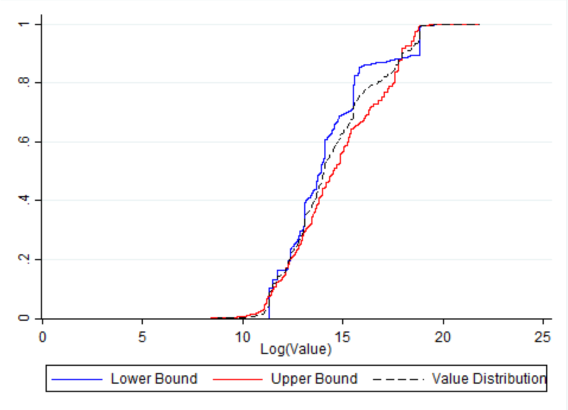


(c) Large Market

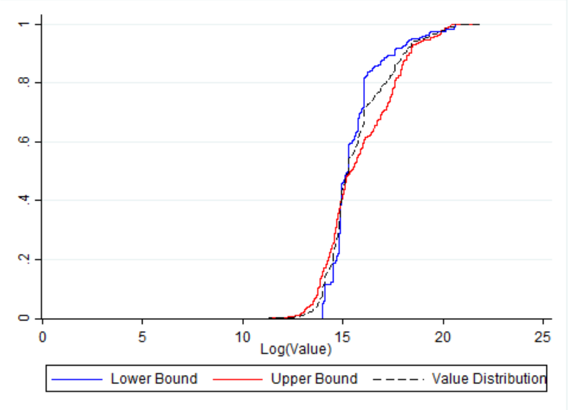
Figure -11: Market-Size Estimation Results, AWS-3 Block G



(a) Small Market

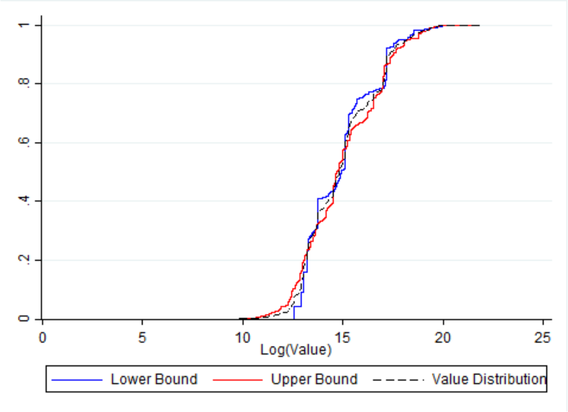


(b) Medium Market

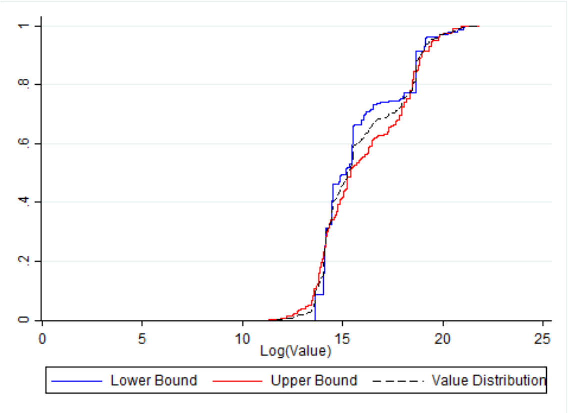


(c) Large Market

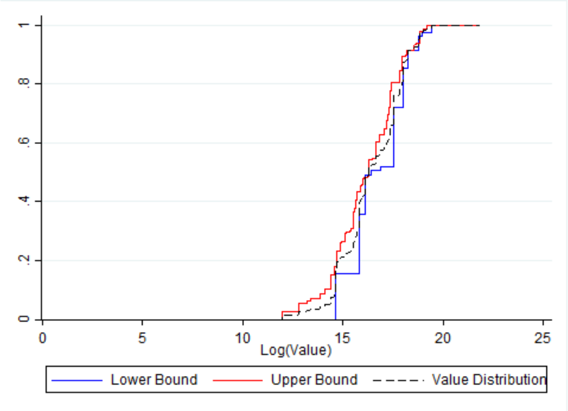
Figure -12: Market-Size Estimation Results, AWS-3 Block H



(a) Small Market

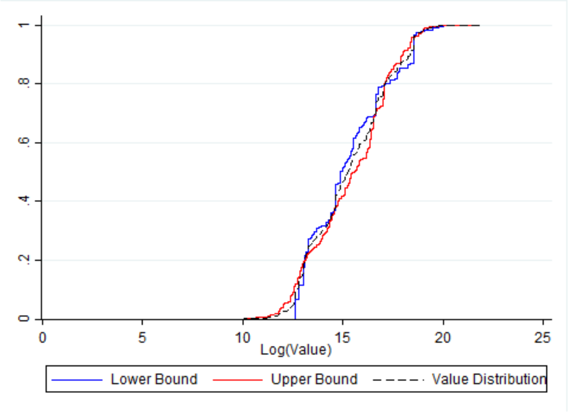


(b) Medium Market

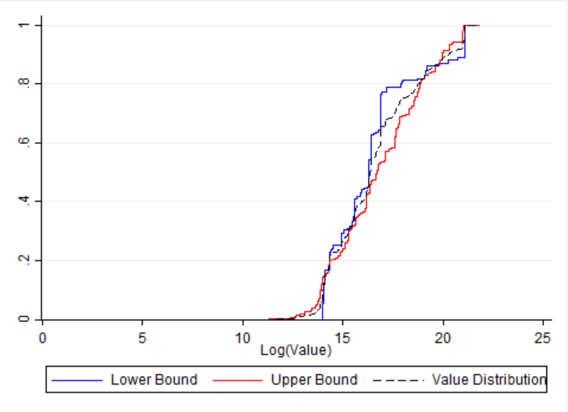


(c) Large Market

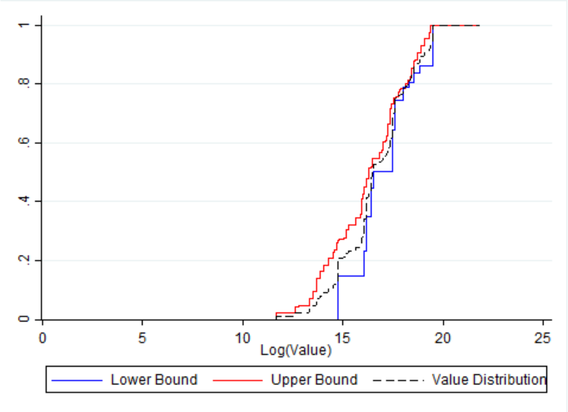
Figure -13: Market-Size Estimation Results, AWS-3 Block I



(a) Small Market

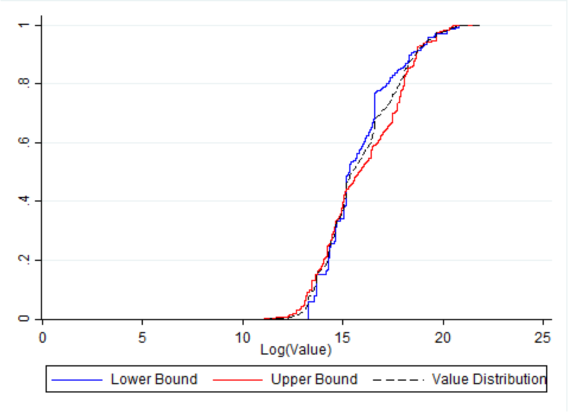


(b) Medium Market

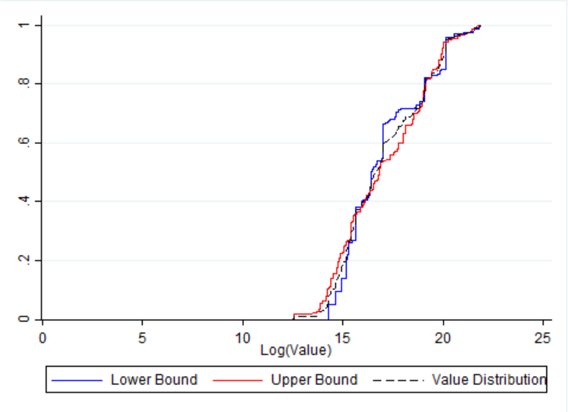


(c) Large Market

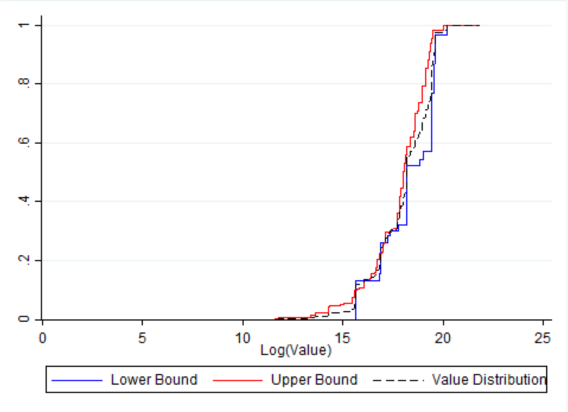
Figure -14: Market-Size Estimation Results, AWS-3 Block J



(a) Small Market



(b) Medium Market



(c) Large Market

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