Evaluation of the Impact of New Rules in FCC's Spectrum Incentive Auction

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Honors Thesis submitted in partial fulfillment of the requirements for Graduation with Distinction in Economics in Trinity College of Duke University.

Duke University
Durham, North Carolina
2018

Acknowledgements

We would like to thank our primary thesis advisor Professor Michelle Connolly for her invaluable guidance during this thesis writing process. Without her support and patience, this project would not have been possible. We would also like to thank our seminar instructor Professor Grace Kim for her insightful comments and suggestions. Furthermore, this paper would not be as comprehensive without the contributions of our fellow researchers in the Spectrum Lab. Finally, we would like to extend our gratitude towards the other students in our Honors Thesis Workshop for their feedback throughout this process.

Abstract

On March 29, 2016, the FCC initiated its first ever two-sided spectrum auction. The auction closed approximately one year later, having repurposed a total of 84 megahertz (MHz) of spectrum. The "Incentive Auction" included three primary components: (1) a reverse auction where broadcasters bid on the price at which they would voluntarily relinquish their current spectrum usage rights, (2) a forward ascending clock auction for flexible use wireless licenses which determined the winning bids for licenses within a given geographic region, and (3) an assignment phase, where winning bidders from the forward auction participated in single-bid, second price sealed auctions to determine the exact frequencies individual licenses would be assigned within that geographic region. The reverse auction and the forward auction together constituted a "stage." To guarantee that sufficient MHz were cleared, the auction included a "final stage rule" which, if not met, triggered a clearing of the previous stage and the start of a new stage. This rule led to a total of four stages taking place in the Incentive Auction before the final assignment phase took place. Even at first glance, the Incentive Auction is unique among FCC spectrum auctions. Here we consider the estimated true valuation for these licenses based on market conditions. We further compare these results to more recent outcomes in previous FCC spectrum auctions for wireless services to determine if this novel auction mechanism impacted auction outcomes.

JEL Codes: L5, O3, K2, D44, L96

Keywords: Incentive Auction, Broadcast Spectrum, Spectrum, Spectrum Reallocation, FCC Auctions

1. Introduction

1.1 Introduction

Since 1994, the Federal Communications Commission (FCC) has been auctioning licenses for electromagnetic spectrum to qualified companies or individuals (FCC, 2006). Spectrum is the set of radio frequencies that serve as inputs into the provision of wireless services. Specific frequencies within a given geographic area are bundled into licenses, which are then used by telecommunication firms and other companies to broadcast signals. Since 1994, the FCC has conducted 89 spectrum auctions (FCC, 2015a).

The most recent auction was the 2016 Broadcast Incentive Auction, the first two-sided spectrum auction conducted by the FCC. While prior auctions had only focused on demand for spectrum exogenously offered by the FCC, the Incentive Auction considered supply-side dynamics as well. This auction sought to repurpose spectrum in the 600-700 MHz range originally provided to TV broadcasters through free, renewable licenses. The two-sided auction was designed to see at what price broadcasters would agree to voluntarily relinquish all or part of their spectrum usage rights, allow the FCC to repackage relinquished licenses into contiguous spectrum, and then sell them as flexible-use licenses to mobile broadband providers.[1] This was intended to "... benefit consumers by easing congestion on wireless networks, laying the groundwork for 'fifth generation' (5G) wireless services and applications" (FCC, 2017a, "A Groundbreaking Auction to Realign Use of the Public's Airwaves").

The Incentive Auction took just over a year to complete, starting on March 2, 2016 and ending on March 30, 2017. In total, 84 MHz of spectrum was repurposed in the auction, 70 MHz

[1] Although spectrum licenses are limited in duration, they are routinely renewed. While the Communications Act of 1934 states that licenses do not convey property rights *per se*, broadcasters have controlled their channels for so long that broadcasters argued that they had at least some *de facto* property rights.

of which was repackaged into licenses to be sold.[2] The auction generated $19.8 billion in revenue ($19.3 billion net of requested bidding credits), $10.05 billion of which was paid to TV broadcasting stations to repurchase spectrum rights, $7.3 billion of which was deposited into the U.S. Treasury, and the rest of which was used to cover the costs of running the auction (FCC, 2017c).

1.2 Structure of Paper

This study is the first to evaluate if and how the novel structure of the Incentive Auction affected final values assigned to spectrum. We contribute to the standing body of literature in four ways.

First, this paper clarifies the Incentive Auction's structure, rules, and provisions for smaller bidders. We compare these to previous spectrum auction designs and highlight differences that may affect bidding outcomes. Next, we investigate the impact of designated entity bidding credits for both small and rural bidders on the final clock price for each market in the forward phase of the Incentive Auction through the **Forward-DE Model**.

Third, we create a more accurate metric for bidder valuation in the **Baseline Valuation Model**. We take advantage of the assignment phase's generalized second-price sealed-bid auction mechanism,[3] and combine assignment phase bids with forward auction prices to create a theoretical measure for bidder valuation.[4]

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[2] 70 MHz for licensed use, and 14 MHz for wireless microphones and unlicensed use

[3] The FCC defines the assignment phase's generalized second-price approach as one in which the bidder pays an amount which, "if the winning bidder had bid that amount, would have been just sufficient to result in the bidder receiving the same winning frequency-specific license assignment." (FCC, 2015b, p. 120).

[4] The accuracy of our estimates is negatively impacted by the fact that licenses in different PEAs were in certain cases grouped during the assignment phase.

Fourth, in the **Comparison Model,** we study the Incentive Auction outcomes in the context of previous spectrum auctions, in conjunction with work by Connolly et al. (2017). We first generate predicted prices based off Connolly et al.'s (2017) model of spectrum valuation, and compare them to the headline winning bids in the Incentive Auction. From there, we create a combined regression model that includes data from both the Incentive Auction and previous auctions, evaluating how the unique changes in the structure of the Incentive Auction might have affected headline winning bids.

The remaining sections of our paper are structured as follows. Section 2 details the procedure of the Incentive Auction and highlights key differences from previous spectrum auctions. Section 3 summarizes existing literature on spectrum valuation and auction design. Section 4 covers the empirical framework of the paper: the methodology behind the models, explanation of variables used, and data sources. Section 5 presents our results and discussions. Finally, section 6 summarizes our findings, and highlights potential implications for future FCC auctions.

2. FCC Auction Design: Incentive Auction & Previous Auctions

2.1 Incentive Auction Mechanism

The Omnibus Budget Reconciliation Act (1993) granted the FCC the authority to hold competitive spectrum auctions. Since 1994, the FCC has primarily conducted forward auctions using the Simultaneous Multi-Round Ascending (SMRA) structure. In SMRA auctions, bidders make bids on individual licenses over multiple rounds. The price of each license rises over these rounds, and the auction is only complete when no more bids are made on *any* license (Brunner et al., 2006). Usually, SMRA auctions were used to allocate licenses with a predetermined frequency range and geographic boundary.

In contrast, the Incentive Auction is a two-sided auction with three parts: (1) a reverse auction with a descending clock; (2) a forward auction with an ascending clock for a generic license within a geographic area; and (3) an assignment phase through a second-price sealed bid, which occurs only after the reverse and forward auctions are complete.

Reverse Auction: The reverse auction seeks to "… determine the price at which broadcasters will voluntarily relinquish their spectrum usage rights" (FCC, 2017b, "A Novel Design"). The reverse auction starts off with an initial clearing target (i.e. amount of spectrum to repurpose). Broadcasters can choose to accept a bid for the option to move to a different frequency, share a channel, or completely give up their spectrum rights and go off-air. The reverse auction takes the format of a descending clock auction. Prices decrease with each round, until the number of channels that Broadcasters are willing to move from or give up no longer supports the initial clearing target. At this point, the reverse auction ends (FCC, 2015).[5]

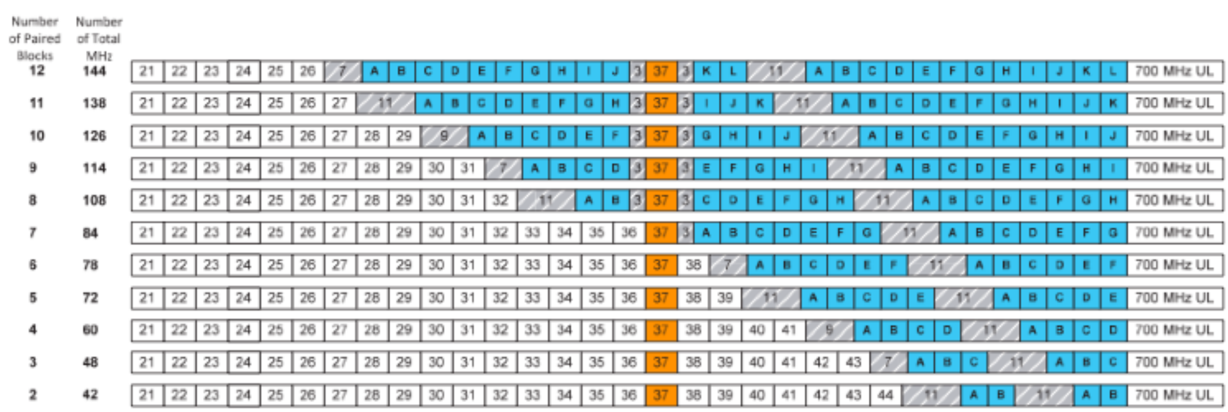
Reorganization & Forward Auction: After repurchasing spectrum rights from broadcasters, the FCC repackages them into standard licenses to be auctioned. These licenses in the 600 to 700 MHz range are organized geographically by Partial Economic Areas (PEAs), which divide the country into 416 service areas.[6] Each license in a PEA is standardized at 10MHz, comprising of a paired 5MHz uplink and 5MHz downlink portion, and licenses are labelled alphabetically based on their exact frequency (see Figure 1). Henceforth, we refer to frequency-specific licenses

[5] For more details, see Appendix A.
[6] See Appendix B for a map of the PEA boundaries.

as blocks. The total number of licenses sold depends on the total amount of spectrum cleared at the end of the reverse auction. Licenses are also subdivided into categories based on impairments, measured by the percentage of a PEA's population that may be subject to interference. Category 1 (C1) licenses are those with potential impairments of up to 15%, and Category 2 (C2) licenses are those with potential impairments between 15% and 50%.

Figure 1: License Labels and Band Plan Scenario (FCC, 2015b, para. 6)

The numbered blocks represent TV channels, and the lettered blocks represent a standard paired license (5MHz uplink + 5MHZ downlink). The shaded blocks are guard bands and duplex gaps, and the numbers represent their sizes in MHz.



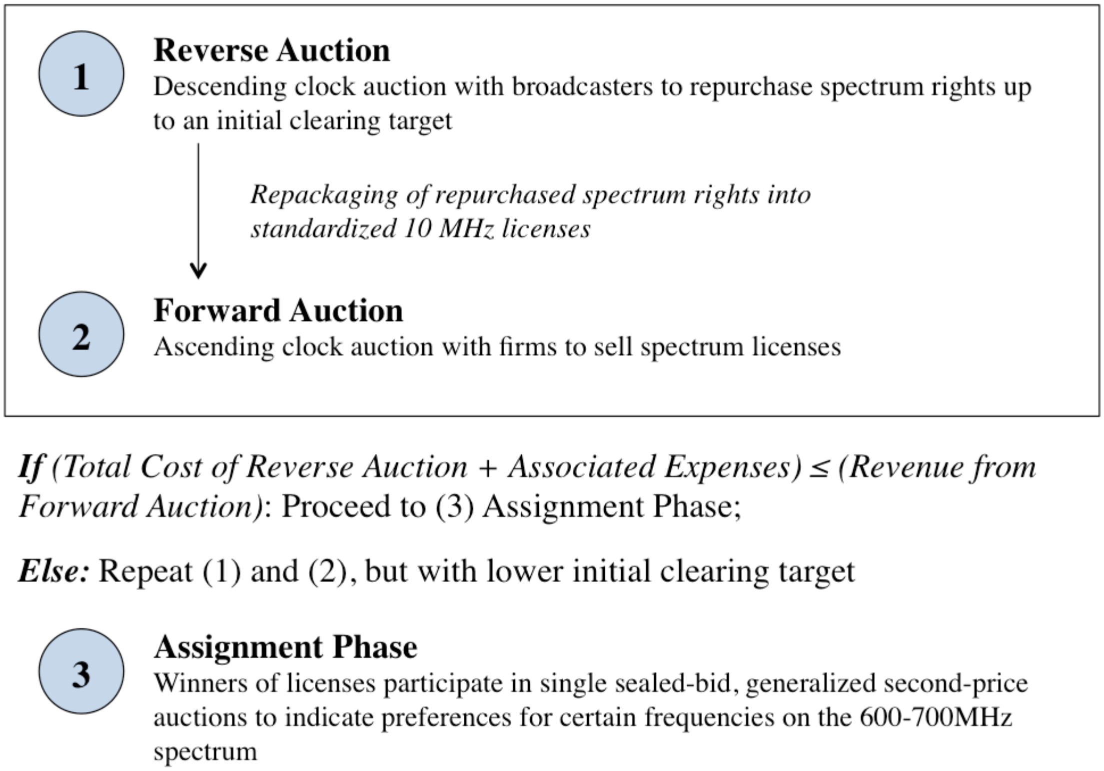
After repacking the licenses, the FCC conducts the forward auction to "…determine the price companies are willing to pay for flexible use wireless licenses" in each geographic area (FCC, 2017b, "A Novel Design"). Bidders indicate their demand for licenses in a given geographic region in an ascending clock auction. In a clock auction, all bidders commit to paying the same price – the clock price - for a license in a given geographic area. As long as demand for licenses exceeds supply, the clock price increases in each round until demand equals supply and the winners are determined. At the end of the forward auction, bidders know how many licenses they have won in each geographic region, but not the exact frequency of those licenses (i.e. the exact block).

Unlike previous spectrum auctions which were one-sided forward auctions, the Incentive Auction is not only two-sided, but further creates a relationship between the reverse and forward auctions due to the implementation of the *final stage rule*. In brief, the final stage rule requires that the forward auction produce enough revenue to cover reverse auction costs and associated expenses, subject to a minimum price predetermined by the FCC.[7] If the final stage rule is not satisfied, the reverse auction begins a new "stage," this time with a lower initial MHz clearing target than before. This brings down the total costs of the reverse auction, and allows the final stage rule to be more easily satisfied. Winners of both the reverse and forward auction are only finalized when this rule is met.[8] At this point, the Incentive Auction proceeds to the assignment phase which determines the exact blocks that winners of the forward auction will hold.

[7] See Appendix A for more details on the final stage rule.

[8] Winners in the reverse auction are television broadcasters who have agreed to sell their channels to the FCC for some price, while winners in the forward auction are mobile telecommunication companies that have agreed to buy a license for some winning bid.

Figure 2: Structure of the Incentive Auction



Assignment Phase: In the assignment phase, bidders bid for specific blocks (frequencies) in a generalized second-price sealed bid auction. Bidders that win at least one license within a PEA are allowed to bid on various configurations of contiguous blocks.[9] By allowing winning bidders to submit preferences over specific block(s), bidders can bid on the same specific frequencies in multiple PEAs in order to "…deploy service using the same frequencies across multiple markets or regions," generating geographical complementarities (Epstein and Kiddoo, 2017, "Assignment Phase").[10]

[9] For example, if bidder X won 4 licenses in a PEA, they would be presented with four possible block configurations to submit optional bids on: {ABCD}, {BCDE}, {CDEF}, and {DEFG}. These options can only be contiguous, i.e. the auction system does not allow bidder X to place a bid on disjoint options like {ABC, E}.

[10] Geographical complementarities refer to the additional value created by owning licenses in two contiguous geographic areas. We further discuss this advantage in Section 2.3.

Sometimes, individual PEAs are combined into "PEA groups" if the same combination of bidders wins the same number of licenses in all the PEAs within a group.[11] The assignment phase bids are then conducted either on individual PEAs, or on these PEA groups where possible. When bidders submit a bid on a PEA group, they are thus indicating their willingness to purchase the same set of frequencies in all PEAs in the group.[12]

After receiving all bids, the auction system "…select[s]...that configuration...for which bidders indicate the greatest willingness to pay," and uses a second-price approach to "… calculate a payment amount that, if the winning bidder had bid that amount, would have been just sufficient to result in the bidder receiving the same winning frequency-specific license assignment" (FCC, 2015b, para. 250, 256). Thus, even when receiving their first-choice allocation, bidders may pay less than their bid amount.

2.2 Discounts & Provisions

Bidding Credits: FCC spectrum auctions have traditionally included provisions and discounts for designated entities (DEs), which refer to "small businesses (including businesses owned by members of minority groups and/or women), rural telephone companies, and eligible rural service providers" (Designated Entities, 2010). DEs were previously determined exclusively based on the average annual gross revenues of bidders for the preceding three years.[13] However, in the Incentive Auction, small bidders are differentiated from rural bidders. While small bidders

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[11] For example, if bidders X, Y and Z respectively win 3, 2 and 1 licenses in the same three PEAs, these PEAs are then grouped into a single "PEA group" for the assignment phase. Only the total quantity of licenses won in the PEA is considered, it does not matter if the licenses were reserved or unreserved.

[12] Continuing from the example in footnote (12), consider now if bidder X had instead won 4 licenses in a PEA *group* (with markets P1, P2, P3), for a total of 12 licenses. Thus, bidder X's bid on the option {ABCD} would apply simultaneously to all markets, and indicate its willingness to be located on that portion of the spectrum for *all* markets P1, P2, and P3; i.e. bidder X would not be able to bid separately by asking for {ABCD} in P1 and {CDEF} in P2 and P3.

[13] In previous auctions, small businesses were eligible for discounts of 15%, 25%, or in some auctions 35%.

continue to be defined based on their average revenue over the last three years, rural providers are determined based on their subscriber count and service areas.[14] Rural providers now qualify for a 15% bidding credit, while small businesses qualify for either a 15% or 25% bidding credit, depending on their average annual gross revenues.[15] Even if a provider qualifies as both a small business and a rural provider, these credits cannot be combined. Finally, bidding credits are applied to both forward auction and assignment phase payments (FCC, 2015b).

Set-Aside Licenses**:** In previous auctions, certain licenses were set-aside for “entrepreneurs,” defined as entities who have gross revenues less than $125 million in the two previous years, and had less than $500 million in total assets (CBO, 2005). In contrast, the Incentive Auction sets aside licenses for “reserve-eligible” bidders. A reserve-eligible bidder in a given PEA is defined as one who either: (a) is a non-nationwide service provider; or (b) is a nationwide provider holding less than 45MHz of spectrum in frequencies below 1GHz in that PEA.

In previous auctions, the number of licenses set-aside was predetermined. However, in the Incentive Auction, the number of licenses set-aside as “reserved” depends on the final clearing target reached by the auction. For example, a clearing target between 70-100 MHz would set aside a maximum of 30MHz of licenses (3 licenses) to be marked as “reserved”; but a 60MHz clearing target would only set aside a maximum of 20MHz of licenses (2 licenses).

Furthermore, set-aside licenses in previous auctions were open only to eligible entrepreneurs from the very *beginning* of the auction. However, “reserved” licenses in the Incentive Auction are only set aside *after* the final stage rule has been met. At this point, licenses

[14] A rural provider is defined as a provider that has 250,000 or fewer subscribers and serves primarily rural areas.
[15] A small business is only eligible for a 15% bidding credit if its average annual gross revenues for the preceding three years does not exceed $55 million. A small business is eligible for a 25% bidding credit if its average annual gross revenue for the preceding three years does not exceed $20 million.

in the forward auction are split into reserved (R) and unreserved (U) statuses. At the split, R and U licenses in each PEA will have separate round clock prices, and may thus end up at different final prices.[16]

Table 1: Summary of Key Differences

Feature	**Incentive Auction**	**Previous Auctions**
Design	Two-sided auction (reverse auction, forward auction) using clock prices.	Forward auction using SMRA.
Quantity of licenses	Endogenously determined once final stage rule is satisfied.	Determined prior to auction.
License Frequency	Licenses in forward auction are generic; specific frequencies are determined later through assignment phase bidding.	Each license offered has a predetermined frequency.
Cost of licenses	All licenses within a PEA which have the same reserve-eligibility (U or R) and license category (C1 or C2) have the same final clock price in the forward auction. Depending on the outcome of the assignment phase, bidders may pay an additional amount for specific frequency allocations.	Each license has its own winning bid.
Designated Entities	Bidding credits for small businesses & rural providers.	Bidding credits for small businesses only.
Set-Aside licenses	An undetermined number of licenses are set-aside for "reserve-eligible" bidders, who can make use of this reserve only when the final stage rule is met.	A predetermined number of licenses are set-aside for "entrepreneurs", who are the only bidders that can bid on these licenses from the beginning.

[16] Once licenses are divided in 'Reserved' (R) and 'Unreserved' (U) in a PEA, the demand within each R and U market will determine the bidding increments and changes in their round clock prices. Thus, the round clock price of R licenses might end up lower than the U licenses in the same PEA. Bidders who are reserve-eligible and bidding on R licenses can simultaneously bid on U licenses in the PEA.

2.2 Incentive Auction Outcomes

The 2016 Incentive Auction occurred over 4 stages (reverse-forward auction iterations). Stage 1 had 27 clock rounds, Stage 2 had 1 clock round, Stage 3 had 1 clock round, and Stage 4 had 58 clock rounds. The final stage rule was met in Stage 4 Round 2, at which point there were only C1 licenses in the auction (no licenses with higher impairment had been cleared in the reverse auction), and these C1 licenses were then split up into C1-R and C1-U licenses. None of the final C1 licenses had any impairments, and hence no impairment discounts were given.[17]

In total, 2776 licenses were sold to 50 different bidders. 1223 of these licenses were reserved, and the other 1553 licenses were unreserved. There were 24 rural providers and 15 small businesses, who won 185 and 260 licenses respectively. 11 regular bidders thus won majority of the licenses (2331 licenses).[18] Among these regular bidders, T-Mobile was the biggest winner, purchasing a total of 1525 licenses for almost $8 billion.[19]

3. Existing Literature

3.1 Spectrum Valuation

A number of papers have examined the impact of license, market, and geographic traits on spectrum auction values. Several papers have confirmed the importance of market-related demand factors, such as population, income, and population density (Ausubel et al., 1997; Moreton and Spiller, 1998; Hazlett, 2008; Bohlin et al., 2010; Wallsten, 2013; Connolly et al., 2017).

[17] See Appendix A for more details about the process of achieving the final stage rule.
[18] See Appendix D.1 for more details about small and rural bidder outcomes.
[19] See Appendix D.2 for more details about the biggest winners of the auction.

Connolly et al. (2017) control for license and block specific auction rules, as well as controlling for different types of technological advancements. The paper relies on Broadband PCS, Narrowband PCS, 700 MHz, and AWS auction data, and demonstrates the negative effects on winning bids of ‘closed’ license provisions, bidding credits, and open access requirements.[20] In contrast, Ayres and Cramton (1996) argue that affirmative action bidding credits in the 1994 regional narrowband auction actually increased government revenue through increased competition. Connolly et al. (2017) also demonstrate the positive effects of bandwidth and paired spectrum on value, which follows other empirical papers (Wallsten, 2013).

Other empirical specifications have investigated geographic complementarities, which refer to the advantages in holding two or more geographically adjacent licenses. Mobile providers may find this more valuable, as it allows them to offer mobile users a larger area of continuous coverage, reduce interference, or benefit from economies of scale. Ausubel et al. (1997) demonstrate strong evidence that geographic complementarity increases license valuation in the first two Broadband PCS auctions, Auctions 4 and 5. Their model regresses geographic complementarity metrics on final headline prices, demonstrating that marginal bidders (those who drop out last) pushed up prices on licenses if they owned or ultimately won adjacent licenses. Moreton and Spiller (1998) use a different estimation technique to examine the same two auctions, and also find strong evidence that geographic complementarity increases license valuation. Although Fox and Bajari (2013) use structural estimation to evaluate the allocative efficiency of Auction 5, they determine spectrum value by measuring geographic complementarity.

[20] See also Dippon (2009), who finds evidence that set-aside provisions were responsible for premiums in the Canadian AWS auction.

3.2 Auction Design

Since the announcement of the FCC's plans to launch a two-sided Incentive Auction, various theoretical papers on the efficiency of these two-sided auctions have emerged (Milgrom et al., 2012; Milgrom & Segal, 2015; Loertscher et al., 2015; Doraszelski et al., 2016).

The Incentive Auction's format of a forward auction combined with an assignment phase closely mirrors a Combinatorial Clock Auction (CCA). Ausubel and Baranov (2017) describe the CCA format as typified by a multiple round clock auction followed by a supplementary sealed-bid round. Sometimes an additional third "assignment" round is needed if the first two rounds treat closely related goods as homogeneous. Cramton (2013) suggests that CCAs may offer advantages over SMRAs by improving the price discovery process, since SMRAs create incentives for bidders to artificially reduce their demand in order to win at lower prices, or engage in tacit collusion or complex bidding strategies. Clock auction formats might prevent such collusive strategies, by only reporting anonymous, aggregate information after each round (Cramton, 2013).

The assignment phase of the Incentive Auction is similar to a Vickrey auction. A Vickrey auction is sealed-bid, second-price auction, where bidders submit a bid without knowing the bids of other participants. The highest bidder wins, but pays the price of the second-highest bid. In such auctions, regardless of whether bidders have the same preferences and independent of others' bidding plans, the weakly dominant strategy is for players to bid their true valuations (Hickman et al., 2012). Thus, the Incentive Auction may be more efficient, in the sense of revealing true valuations, than most previous FCC auctions.

3. Empirical Methodology

3.1 Forward-DE Model

Our first model explores the impacts of designated entity (DE) bidding credits for small and rural bidders on the outcome of the forward auction, as measured by the final clock prices for reserved and unreserved licenses in a given PEA.

As compared to previous spectrum auctions, the Incentive Auction makes use of an ascending clock auction to determine a large part of the final price paid by bidders for a license (the only additional cost being an optional bid in the assignment phase). Since DEs only apply their credits at the end of the auction, during the forward auction process DEs can bid prices higher than their true valuations. Furthermore, the Incentive Auction is the first to provide bidding credits to rural providers.

Here we attempt to evaluate the competitive and efficiency effects of providing bidding credits to both small businesses and rural providers. For each license type (U or R) in a PEA, we create the following measures for bidders: their total number, the percentage who were small/rural, and the percentage of winning bidders who were small/rural. We also create simple dummy variables to indicate whether a small/rural bidder was present or was a winning bidder within a particular license type in a PEA.

The model uses the following general expression for each license category *j* in PEA *i*:

$$\begin{aligned} ClockPrice_{ij} = \alpha + \vec{\beta}\left(\overrightarrow{Market\ Traits}\right)_i + \gamma_1(Reserved\ Category)_j \\ + \gamma_2(Number\ of\ Bidders)_{ij} + \vec{\delta}\left(\overrightarrow{Small\ \&\ Rural\ Bidder\ Measures}\right)_{ij} + \varepsilon \end{aligned}$$

3.2 Baseline Valuation Model

We then construct a measure for spectrum valuation by combining forward auction clock prices and assignment phase bids. We regress these valuations on market and license traits, auction characteristics, and the small and rural bidder metrics.

Modeling Valuation: We hypothesize that a bidder's true valuation for a set of licenses in a given market can be inferred from the sum of the total forward auction clock price (which is identical for all licenses of the same type in a given market) and the assignment phase bid placed on the specific frequency of the license.

Although some literature suggests that clock auctions might be more efficient than SMRAs (Cramton, 2013), the forward auction clock prices alone are not reliable measures of a bidder's valuation of a license, since the forward auction only grants license rights to a generic license (i.e. winning bidders in a market pay the same license price for each license type).

Given the theoretical finding that the weakly dominant strategy in Vickrey auctions (assignment phase) is for bidders to report their true valuation, we add assignment phase bids for specific block frequencies to the forward auction clock prices. We use the values of *bids* placed rather than final *payments*, since bids should reflect true valuation, whereas payments correspond to the second-best price. Bidders submit bids on several different frequency combinations. We, however, focus only on bids corresponding to the final outcome of the auction to prevent the regression from being skewed towards outcomes in license markets where there are more bids.[21]

[21] For example, if bidder A won 3 licenses in market M1 and submitted bids on blocks {ABC, CDE, EFG} for the corresponding bids of {15, 10, 5} but eventually was only allocated blocks {CDE}, we would consider only {CDE} for a value of 10. Considering only the final outcome would prevent overweighting of markets where, for example, 7 bidders won 1 license each, and each bidder had submitted preferences for each block from A to G. This would create 49 observations for the market as opposed to much less in other markets.

Importantly, the assignment phase bid acts an "overflow" to capture any excess valuation above the forward auction clock price. In the following three scenarios, we demonstrate how the sum of the forward auction clock price (*CP*) and the assignment phase bid (*B*) should equate to valuation (*V*):

(a) ***CP* > *V*:** If *CP* > *V*, the bidder would have dropped out of the forward auction, and would not be included in our data. That is, for $V = \{V_i\}$, the set of valuations for a single license in frequency blocks $i \in \{A, B, C, D, E, F, G\}$, $CP \leq \min(V_i)$, for a bidder to remain in the auction.

(b) ***CP* = *V*:** If *CP* = *V*, then the bidder would only set a value for *B* at 0, since he has already maxed out his valuation for the license in the forward auction. Thus, the final price is *CP* + 0 = *V*.

(c) ***CP* < *V*:** If the *CP* < *V*, then the bidder could set a value for *B* up to *(V - CP)*. Since the structure of the assignment phase incentivizes bidders to bid their true valuation, the bidder will set *B = (V - CP)* and the combination of the forward auction *CP* and assignment phase *B* will be *CP* + *B* = *CP* + (*V* - *CP*) = *V*.

Lastly, we discount for bidding credits. Thus, for bidder b, the valuation for a set of licenses i in market j, that occur on frequencies k, is

$$Valuation_{bijk} = [(Number\ of\ Licenses * Forward\ Auction\ Clock\ Price)_{bij} + \left(Adjusted\ Assignment\ Phase\ Bid\right)_{bijk}\big] * [1 - (Bidding\ Credit)_b]$$

Method for Adjusting the Assignment Phase Bid: Although our model looks at the value of licenses in a given market, some assignment phase bids were placed over multiple PEAs, in the "PEA group" bidding. This means that in the case of PEA groups, we only observe the assignment bid that a firm is willing to pay for a particular block (or groups of blocks) knowing that this assignment will hold across all the PEAs in that group. Hence, we had to decide how to assign the value of the assignment bid for a PEA group across the individual PEAs within that group.[22]

To break down the PEA group assignment phase bids into separate values for each PEA in the group, we create a GDP weighted index. In this index, each PEA is assigned a GDP value, equal to the product of its real median income and population. These GDP values are then used to establish the relative value of each PEA within its PEA group.[23] We use these weights to disaggregate the group-level assignment phase bids into market-level bids.

Assume that bidder *i* makes an assignment phase bid on PEA group *k*, $(\text{Bid})_{ik}$. PEA group *k* contains some combination of PEAs *j,* for n(j) > 1. In our model, bidder *i* is said to bid $(\text{Adjusted Assignment Phase Bid})_{jk}$ on PEA_j according to the equation below:

$$(Adjusted\ Assignment\ Phase\ Bid)_{ijk} = (Bid)_{ik} * \left(\frac{GDP_j}{GDP_k}\right)$$

where $GDP_k = \sum_{j \epsilon k} GDP_j$

[22] One option would be to aggregate the PEAs and analyze outcomes at the PEA group level. The other option is to apply some weighting rule to disaggregate the assignment bid for the PEA group and appropriate it to individual PEAs. Both have advantages and disadvantages. The forward clock prices are PEA specific, while the assignment bids are often PEA group specific. Hence, noise will be introduced whether aggregating up to PEA groups or disaggregating from PEA groups to individual PEAs.

[23] A GDP-weighted index treats population and income as equally important determinants of market value. This is therefore imposing a particular assumption about the contribution of each to determining the relative market value of each PEA. Connolly et al. (2017) find reasonably similar estimates for the elasticity of winning spectrum bids with respect to population and real income, suggesting that this may be a reasonable assumption to use.

Empirical Model: The model uses the following general expression for each bidder *k*'s winnings in market *i*:

$$Log(Valuation)_{ik} = \alpha + \vec{\beta}(\overrightarrow{Market\ Traits})_i + \vec{\gamma}(\overrightarrow{License\ Specific\ Characteristics})_{ik} + \vec{\delta}(\overrightarrow{Small\ \&\ Rural\ Bidder\ Measures})_i + \varepsilon$$

License Specific Characteristic - Frequency Block Controls: We include a set of dummy variables to control for the particular frequency of the final license. Since the dependent variable *Valuation* is calculated for a **set** of blocks, dummy variables are coded as 1 for each block in the set.[24]

Small & Rural Bidder Measures: Unlike the Forward-DE model, the dependent variable in the Baseline Valuation model is a package of license(s) that may include a combination of reserved and unreserved licenses. For this reason, instead of measuring small/rural competition metrics by license type (U or R), we calculate the percent of winning small bidders and rural bidders in each PEA, regardless of what type(s) of license(s) they won.

3.3 Comparison Model

The last two parts of our paper compare the outcomes of the Incentive Auction to previous spectrum auctions to evaluate whether the change in auction structure had a tangible impact on auction outcomes. We hypothesize that the major changes such as the inherent uncertainty of the amount of spectrum being cleared (due to the final stage rule), the addition of

[24] For example, if a bidder had won a set of 3 licenses in frequencies {ABC}, the dummies for each of the block controls A, B and C, would be coded as 1.

the assignment phase bidding, and the demarcation of some licenses as "reserved," had a separate and distinct impact on the final headline winning bids.

Dependent Variable - Adjusted Headline Price: Similar to the Baseline Valuation model, we partition PEA group-level assignment phase outcomes down to individual PEA levels using the GDP-weighted method. However, in this section we use assignment phase *payments* instead of *bids*, since the model seeks to compare observed outcomes (and not valuation) across all spectrum auctions. Thus, for each bidder b, the headline price for winning a set of licenses i in market j, that occur on frequencies k, is:

$$\begin{aligned} Headline\ Price_{bijk} &\\ &= (Number\ of\ Licenses * Forward\ Auction\ Clock\ Price)_{bij} \\ &+ (Adjustment\ Assignment\ Phase\ Payment)_{bijk} \end{aligned}$$

Prediction Test: Using the license and auction characteristics from the Incentive Auction dataset, we use Connolly et al.'s (2017) spectrum valuation model to generate predicted prices, and compare that to the observed headline outcomes of the Incentive Auction (adjusted as explained previously). We use paired t-tests to determine if there is a significant difference between the two values.

Combined Model: Next, we combine our dataset with Connolly et al's (2017), which includes headline winning bids and characteristics of 15 different cellular auctions from 1997 to 2015. To explore the effects of the Incentive Auction on final outcomes and other components of spectrum valuation, we use their model and include a dummy variable for the Incentive Auction and interaction effects. In reduced form, we consider the following general expression for each license *i* at time *t*:

$$
\begin{aligned}
Log(Headline\ Winning\ Bid)_{it} \\
&= \alpha + \vec{\beta}(\overrightarrow{Market\ Traits})_{it} + \vec{\gamma}(\overrightarrow{License\ Specific\ Characteristics})_{it} \\
&+ \vec{\delta}(\overrightarrow{Auction\ Level\ Characteristics})_{it} + \vec{\lambda}(\overrightarrow{Aggregate\ Traits})_{t} + \varepsilon
\end{aligned}
$$

3.4 OLS Regressions

For all of the models, we use ordinary least square (OLS) regressions. While previous empirical work considered Tobit models (Bohlin, 2010; Wallsten, 2013), Connolly et al. (2017) found that Tobit and OLS models resulted in similar coefficients. Thus, we focus only on OLS regressions.

3.5 Variables

In addition to the new variables described previously, we adopt all of the variables used by Connolly et al. (2017) in their baseline models. These components of spectrum valuation have also been empirically supported by other studies: market traits like income and population are important indicators of future revenue streams (Ausubel et al., 1997; Moreton and Spiller, 1998; Hazlett, 2008; Bohlin et al., 2010; Wallsten, 2013; Connolly et al., 2017), paired bands tend to be more useful and increase the value of licenses (Connolly et al., 2017; Wallsten, 2013), and lower frequencies tend to be more technologically efficient and attract higher price premiums (Keras et al., 2011). The squared term for bandwidth is included because it is predicted that beyond a certain size, additional bandwidth should have less marginal value.[25]

3.6 Data Sources

Incentive Auction Data: Data on the outcomes of the Incentive Auction come from the FCC's Public Reporting System, which includes all bidder information (designated entity status and bidding credit values), population sizes of each PEA, forward auction bids and clock prices, assignment phase bids, and the final allocation of the licenses (FCC, 2017d). Following Connolly et al. (2017), we similarly use annual county level median income data from the Census Bureau's SAIPES and the country area information from FCC to construct total area and median income measures for every PEA. Bid values and income measures are converted into 2000 US Dollars used the monthly US CPI estimates drawn from the National Bureau of Economic Research (NBER).

Previous Spectrum Auction Data: We draw from Connolly et al.'s (2017) dataset that catalogues over 4,500 observations from 15 auctions that occurred between 1997 and 2015.[26]

[25] See Appendix E for the full list of variables and their descriptions.
[26] Connolly et al. (2017) only consider post 1996 auctions due to various established problems with the outcomes of earlier auctions. See: Kwerel & Rosston (2000). The final auctions included in their paper were: 11, 22, 33, 35, 38, 44, 49, 58, 66, 71, 73, 78, 92, 96, 97.

4. Results & Discussion

4.1 Forward-DE Model

Table 2 presents the results from regression forward auction clock price outcomes on market characteristics and small and rural bidder measures.[27] Specifications (2) and (3) use dummy variables, whereas specifications (4) and (5) use continuous variables measuring the proportion of DE bidders (recorded as values between 0 and 1).

Components of Spectrum Valuation: Across all specifications, the coefficients on population and real median income are positive and statistically significant, as expected. The larger coefficient on population suggests that population is a larger determinant of market value relative to income: this might be due to the income inelasticity of mobile services, given their current ubiquity across all income levels; it is estimated that 95% of Americans currently own a cell phone (Pew Research Center, 2018).

Reserved Type: The coefficient for reserved type does not seem to be consistent across the specifications. This may be because we add controls for rural and small bidders, who are also be classified as reserve-eligible. Furthermore, some of biggest winners of the auction, such as T-Mobile, were actually reserve-eligible in numerous markets, because they did not have substantial existing holdings in these markets.[28] Thus, the reserve might not have had a meaningful effect in this auction, even if it was intended to benefit non-dominant bidders.

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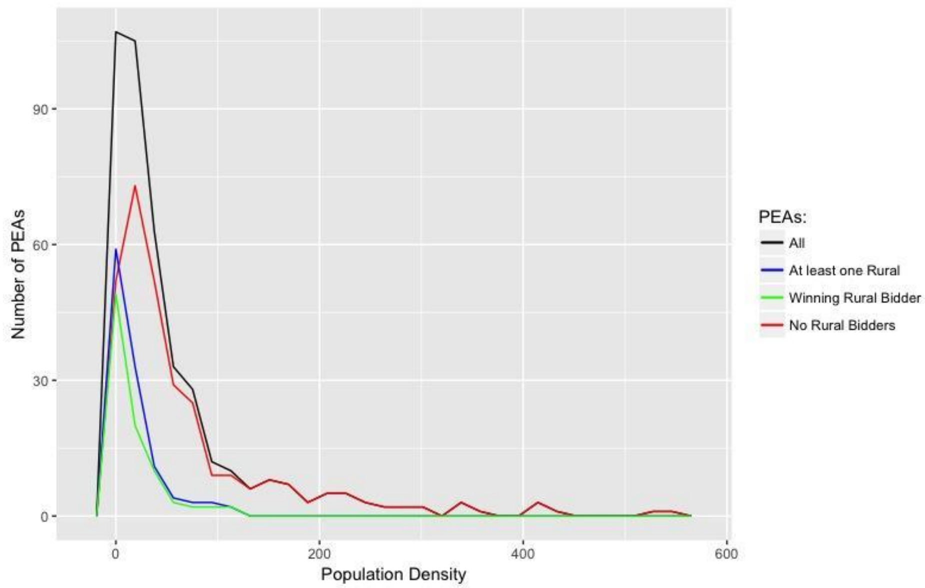
[27] An alternative specification including variables for the number of bidders can be found in Appendix F.
[28] See Appendix D.2 and D.3 for more details about the biggest winners of the auction and the use of reserved licenses.

Table 2: Impact of DE on Forward Auction Clock Prices

	Dependent variable: Log Final Clock Price				
	(1)	(2)	(3)	(4)	(5)
Population (Logs)	1.138***	1.192***	1.169***	1.159***	1.158***
	(0.034)	(0.031)	(0.032)	(0.030)	(0.032)
Population Density (Logs)	0.021	0.093***	0.054**	0.128***	0.059**
	(0.029)	(0.027)	(0.027)	(0.027)	(0.027)
Real Median Income (Logs)	0.708***	1.001***	0.950***	0.974***	0.925***
	(0.156)	(0.144)	(0.146)	(0.141)	(0.146)
Reserved Type	-0.016	-0.035	-0.084*	-0.033	-0.084*
	(0.054)	(0.049)	(0.051)	(0.048)	(0.051)
Presence of Rural Provider (Dummy)		0.592***			
		(0.061)			
Presence of Small Business (Dummy)		-0.450***			
		(0.053)			
Winning Rural Provider (Dummy)			0.499***		
			(0.077)		
Winning Small Business (Dummy)			-0.471***		
			(0.058)		
% of bidders Rural				2.179***	
				(0.211)	
% of bidders Small				-1.174***	
				(0.138)	
% of winning bidders Rural					1.088***
					(0.177)
% of winning bidders Small					-1.089***
					(0.131)
Constant	-8.193***	-12.163***	-11.197***	-11.602***	-10.812***
	(1.653)	(1.543)	(1.560)	(1.498)	(1.558)
Observations	822	822	822	822	822
R^2	0.791	0.827	0.820	0.835	0.819
Adjusted R^2	0.790	0.826	0.819	0.834	0.818
Residual Std. Error	0.774 (df = 817)	0.705 (df = 815)	0.719 (df = 815)	0.687 (df = 815)	0.720 (df = 815)
F Statistic	772.147*** (df = 4; 817)	649.106*** (df = 6; 815)	618.610*** (df = 6; 815)	689.253*** (df = 6; 815)	616.612*** (df = 6; 815)

Small Business versus Rural Provider: Although small businesses and rural providers both qualify as “designated entities,” the results show that the impacts of their presence in the auctions are very different. The negative coefficient for small bidder measures is consistent with previous empirical work which finds that small business winning bidders are associated with lower license prices (Connolly et al., 2017).

Figure 3: Frequency Plot of PEAs by Rural Provider Presence



However, the measures for rural bidders are positive and statistically significant (*Presence of Rural Provider, Winning Rural Provider, % of bidders Rural* and *% of winning bidders Rural*). Figure 3 illustrates the frequency plot of PEAs by population density. The red line represents markets in which no rural bidders participated, and the blue line represents markets in which at least one rural bidder participated. In general, we see that rural bidders tend to lean towards less dense markets. However, in the Incentive Auction, rural providers actually made up a majority of the bidders: out of all 62 bidders registered in the auction, 28 were rural providers. Furthermore, out of the 50 winning bidders, 24 were rural providers.[29] Since higher concentrations of rural bidders were associated with less dense markets, *% of bidders Rural* and *Presence of Rural Provider* may reflect instances in which a relatively large number of bidders compete over a rural market, pushing up prices. Furthermore, the green line in Figure 3 (markets in which at least one rural bidder won a license) illustrates that they also tend to win in these markets, explaining why the variables measuring whether a rural bidder has won (the dummy

[29] See Appendix D.1 for more details on designated entity participation in the Incentive Auction.

Winning Rural Provider and the continuous variable *% of winning bidders Rural)* are also positive. Nevertheless, this impact might be limited in scope, given that these bidders only won 185 licenses in total.

Another observation supporting the hypothesis that the impact of rural bidder participation is limited to lower density markets is the change in significance of the population density measure. Empirically, lower population density tends to depress prices. However, in the base specification, *Population Density (Logs)* is insignificant. It is only after adding controls for rural bidders in specifications (2) - (5) that the coefficients for population density become significant. As Figure 3 illustrates, the participation of rural bidders, which have a positive price effect, tends to occur in lower value PEAs (less dense PEAs). Thus, in the absence of rural bidder controls, the opposing price effects of rural bidder participation and density may cause the coefficient on population density to become insignificant.

4.2 Baseline Valuation Model

Table 3 presents our results on the baseline valuation model.[30] The coefficients on market-level characteristics, including population, population density, and real median income remain consistent with the Forward-DE Model. However, some specific differences merit discussion.

[30] An alternative specification including variables for the number of bidders can be found in Appendix G.

Table 3: Baseline Valuation Model

	Dependent variable: Log Valuation						
	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Population (Logs)	1.097***	1.062***	1.073***	1.081***	1.076***	1.094***	1.110***
	(0.029)	(0.028)	(0.027)	(0.027)	(0.027)	(0.024)	(0.024)
Population Density (Logs)	0.040	0.048**	0.060***	0.063***	0.062***	0.152***	0.110***
	(0.025)	(0.024)	(0.023)	(0.023)	(0.023)	(0.021)	(0.021)
Real Median Income (Logs)	0.589***	0.527***	0.581***	0.606***	0.594***	0.768***	0.797***
	(0.134)	(0.130)	(0.122)	(0.123)	(0.122)	(0.111)	(0.113)
License Bandwidth	0.167***	0.208***	0.183***	0.177***	0.180***	0.158***	0.156***
	(0.013)	(0.016)	(0.015)	(0.015)	(0.015)	(0.014)	(0.014)
License Bandwidth Squared	-0.003***	-0.005***	-0.004***	-0.004***	-0.004***	-0.003***	-0.003***
	(0.0003)	(0.0003)	(0.0003)	(0.0003)	(0.0003)	(0.0003)	(0.0003)
Bidder-Specific Variables							
15% Bidding Credit (Dummy)			0.074				
			(0.078)				
25% Bidding Credit (Dummy)			-0.846***				
			(0.063)				
Rural Provider 15% Bid Credit (Dummy)				0.159*	0.144	-0.347***	-0.353***
				(0.089)	(0.089)	(0.087)	(0.093)
Small Business Bid Credit (Dummy)				-0.768***			
				(0.061)			
Small Business 15% Bid Credit (Dummy)					-0.142	0.123	0.213
					(0.154)	(0.140)	(0.144)
Small Business 25% Bid Credit (Dummy)					-0.848***	-0.573***	-0.472***
					(0.063)	(0.060)	(0.065)
Market-Specific Small/Rural Measures							
% of bidders Rural						2.237***	
						(0.191)	
% of bidders Small						-1.238***	
						(0.121)	
% of winning bidders Rural							1.725***
							(0.194)
% of winning bidders Small							-1.305***
							(0.130)
Frequency Block Controls							
Frequency Block A		0.162*	0.071	0.065	0.072	-0.047	-0.058
		(0.086)	(0.081)	(0.082)	(0.081)	(0.074)	(0.075)
Frequency Block B		0.449***	0.353***	0.496***	0.392***	0.292**	0.311**
		(0.144)	(0.135)	(0.136)	(0.137)	(0.124)	(0.126)
Frequency Block C		0.337*	0.258	0.220	0.256	0.200	0.220
		(0.204)	(0.193)	(0.194)	(0.193)	(0.173)	(0.177)
Frequency Block D		0.512***	0.466***	0.496***	0.479***	0.401**	0.430***
		(0.187)	(0.175)	(0.177)	(0.175)	(0.158)	(0.161)
Frequency Block E		0.696***	0.533***	0.610***	0.552***	0.401***	0.414***
		(0.109)	(0.102)	(0.103)	(0.103)	(0.093)	(0.095)
Frequency Block F		0.132	0.131	0.167	0.148	0.056	0.056
		(0.110)	(0.104)	(0.105)	(0.104)	(0.094)	(0.096)
Constant	-7.958***	-7.243***	-7.559***	-7.887***	-7.719***	-9.783***	-10.151***
	(1.410)	(1.369)	(1.284)	(1.295)	(1.287)	(1.183)	(1.197)
Observations	1,352	1,352	1,352	1,352	1,352	1,352	1,352
R^2	0.779	0.794	0.820	0.818	0.820	0.855	0.849
Adjusted R^2	0.778	0.792	0.818	0.816	0.818	0.853	0.847
Residual Std. Error	0.846 (df = 1346)	0.820 (df = 1340)	0.767 (df = 1338)	0.771 (df = 1338)	0.766 (df = 1337)	0.689 (df = 1335)	0.703 (df = 1335)
F Statistic	950.186*** (df = 5; 1346)	468.714*** (df = 11; 1340)	468.398*** (df = 13; 1338)	461.269*** (df = 13; 1338)	435.671*** (df = 14; 1337)	490.565*** (df = 16; 1335)	469.177*** (df = 16; 1335)

License Bandwidth*:* The model controls for *License Bandwidth* and *License Bandwidth Squared*, which describes how much spectrum a bidder has won in each PEA. *License Bandwidth* is positive and significant, which reflects that bidders have higher values for licenses offering greater quantities of spectrum (Connolly et al., 2017; Bohlin et al., 2010; Wallsten, 2013). However, the coefficient on *License Bandwidth Squared* is negative and statistically significant, indicating that the marginal value of additional spectrum diminishes beyond a certain point.

Block Controls: The coefficients on the block controls for B, C, and D are positive and statistically significant. This may indicate that bidders have preferences for the middle blocks of spectrum. However, bidder preferences for frequencies may depend on their existing spectrum holdings, a variable we were not able to take into account. Furthermore, the dependent variable in the valuation model is a *set of licenses*, not an individual license. Thus, block controls describe the value of a set containing that block, relative to sets that do not contain that block. For this reason, it is difficult to argue that the coefficients on block controls should be interpreted as true bidder preferences for particular blocks.

Rural Bidders: The bidder-specific dummy *Rural Provider 15% Bid Credit* is negative in specifications (11) and (12). These negative coefficients are bigger than one would expect from a 15% bidding credit (i.e. they are more extreme than -0.15). This implies that compared to other winning bidders in the same market, rural bidders still value the license less, even after controlling for bidding credits in the dependent variable.

However, that the market-specific rural bidder measures in specifications (11) and (12) *(% of bidders Rural* and *% of winning bidders Rural)* still have positive and statistically significant coefficients indicate that the composition of bidders in a market might still impact individual valuations. This might indicate that valuations are not entirely independent, although this topic is beyond the scope of this paper.

4.3 Comparison of Incentive Auction with Previous Cellular Auctions

Table 4: Paired T-Test Results
H_0: True difference in means = 0; H_1: True difference in means =/= 0
Difference = Observed - Predicted

	Mean of differences	**T-Value**	**P-Value**	**95% C.I.**
Model 3 (Modified)	1.41399	12.504	< 2.2e-16	1.192161, 1.635819
Model 4 (Modified)	0.8333956	8.6369	< 2.2e-16	0.6441041, 1.0226872

Table 4 presents the results from the paired t-test on the observed versus predicted winning bids and both models show a significant difference, implying that the Incentive Auction might have brought in lower revenues than one would expect from previous auction data.

Figure 4: Prediction Plot from 2007 - 2015 Auctions

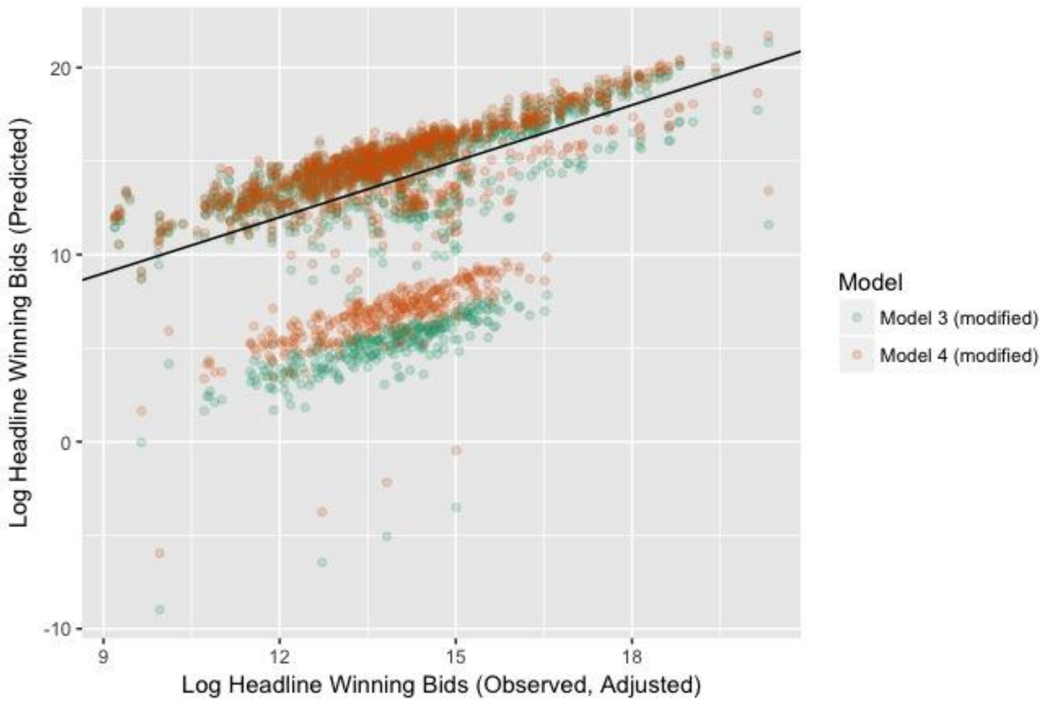
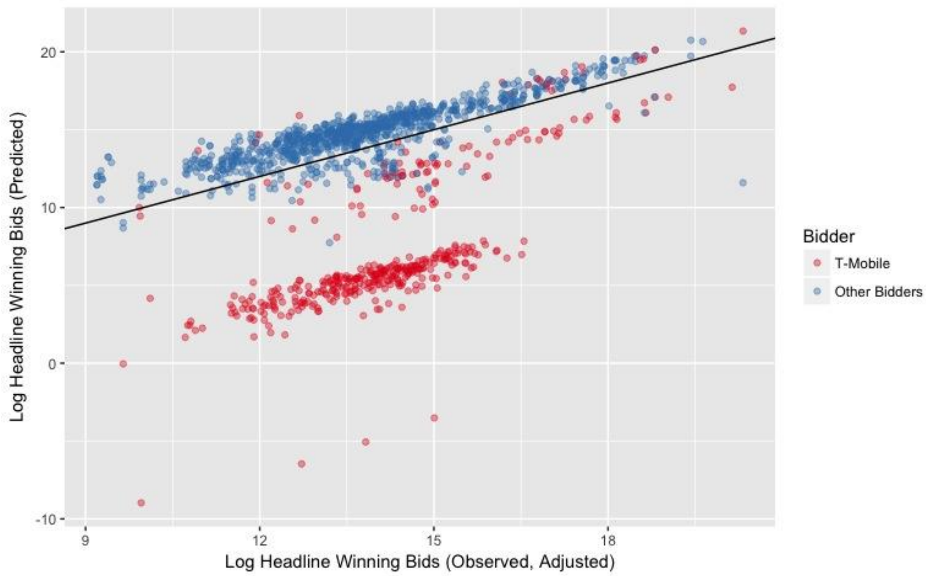


Figure 4 plots the predictions of the two modified models against the observed (adjusted) headline bids from the Incentive Auction. The black diagonal line represents the values for which predictions equal to observed. In general, both models show two clear clusters: one that over-predicts, and one that under-predicts. Even though there are clearly more over-predictions, the degree of over-prediction (Observed - Predicted < 0) is significantly smaller than the degree of under-prediction (Observed - Predicted > 0), which explains the positive means in Table 3

Figure 5: Model 3 (Modified) Prediction Plot, by Bidder

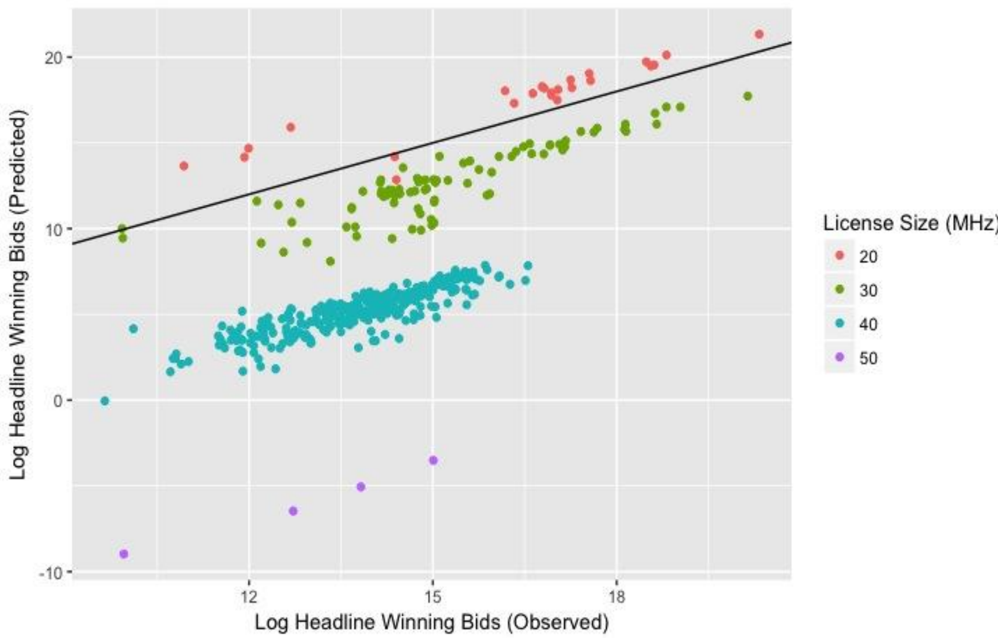


These clusters do not seem to occur based on market trait characteristics, like population, population density, or real median income. While exploring the data, the only variable we identified that systematically predicts whether Model 3 (modified) overpredicts or under-predicts observed values is bidder type (regular, small or rural; see Appendix J). In particular, we suspected that T-Mobile (who won the most licenses in the auction) might be responsible for the clustering. Figure 5 colors the data points based on bidder, and clearly illustrates that the under-predicted values are solely associated with licenses won by T-Mobile. Since the observed values were larger than the predicted values, this implies that T-Mobile paid more than what was expected by Model 3 (modified).

While the previous plot might suggest that T-Mobile could have systematically overpaid for certain licenses, Figure 6 illustrates otherwise. The figure shows a plot of T-Mobile's bids, colored by the license size. The predictions clearly become worse (higher degree of under-prediction) for licenses of bigger bandwidth. The largest license bandwidth size in Connolly et al.'s (2017) original dataset was only 30MHz, and most licenses had bandwidths 10 MHz or less.

However, T-Mobile's bandwidths in the Incentive Auction dataset range from 20 MHz to 50 MHz. Thus, the negative coefficient on *license bandwidth squared* might be over-penalizing larger, out-of-sample license bandwidths, resulting in lower predicted values.

Figure 6: Model 3 (Modified) Prediction Plot, T-Mobile Bids, by License Size



For all other licenses of smaller bandwidth sizes, the figures still show that the predictions tend to be over estimates rather than underestimates. This might thus imply that the Incentive Auction actually resulted in lower headline winning bids than usual. Thus, in our combined model we include a dummy variable for observations from the Incentive Auction.

Table 5 presents the results of this model based on the combined dataset of recent auction data (2007 to 2017). Specifications (14) and (16) - (18) use specific dummies for small businesses and rural providers, as compared to the generic *Bid Credit Used by DE* in specifications (13) and (15), which includes both types of bidders.[31] Specifications (15), (16) and (18) also control for number of bidders and bidders squared.[32] [33]

Components of Spectrum Valuation: While the coefficients' point estimates are different than those in Connolly et al. (2017), the direction of impact and statistical significance remains the same. This reinforces existing findings in the spectrum valuation literature.

License Bandwidth: The sign on the coefficients of *License Bandwidth* and *License Bandwidth Squared* remain consistent with previous models - a positive coefficient on *License Bandwidth* and a negative coefficient on *License Bandwidth Squared*. However, in comparison to the coefficients found by Connolly et al. (2017), which we used to predict and plot in Figures 4-6 above, the absolute value of the negative coefficient on *License Bandwidth Squared* has actually decreased.[34] This is evidence that the prediction model above *did* over-penalize larger, out-of-sample bandwidths. After including new observations with bigger license sizes, the coefficient on *License Bandwidth Squared* has adjusted to reflect that decreasing marginal valuation for license bandwidth only sets in at higher bandwidth values.

[31] Rural providers only received bidding credits in the Incentive Auction, and are defined based on subscriber count rather than revenue (small businesses). Since small businesses are defined by revenue, we choose to treat rural and small bidders separately.
[32] It should be noted that these results remain even when we include all auctions of licenses related to cellular services from 1997 to 2017. We choose to focus on the more recent time period as it should be more predictive of outcomes in an auction that ended in 2017. See Appendix I for results including all observations from 1997.
[33] For all Incentive Auction observations, we choose to set the value for the 'Closed License' dummy to 0. The observations for the Incentive Auction are packages of license(s) that may include a combination of Reserved and Unreserved licenses, and thus cannot be clearly classified as either 'closed' or 'open'.
[34] See Appendix H for coefficients from Connolly et al.'s (2017) modified model that were used to predict prices.

Table 5: Combined Model with All Cellular Auctions, 2007-2017, including Incentive Auction

	Dependent variable: Log Real Headline Price (2000 dollars)					
	(13)	(14)	(15)	(16)	(17)	(18)
Population (Logs)	1.158***	1.158***	1.142***	1.142***	1.162***	1.147***
	(0.015)	(0.015)	(0.015)	(0.015)	(0.015)	(0.015)
Population Density (Logs)	0.079***	0.091***	0.062***	0.073***	0.089***	0.071***
	(0.012)	(0.012)	(0.012)	(0.012)	(0.012)	(0.012)
Real Median Income (Logs)	1.000***	1.033***	0.908***	0.943***	1.033***	0.929***
	(0.077)	(0.076)	(0.075)	(0.075)	(0.076)	(0.075)
License Bandwidth	0.187***	0.175***	0.182***	0.171***	0.176***	0.175***
	(0.009)	(0.009)	(0.009)	(0.009)	(0.009)	(0.009)
License Bandwidth Squared	-0.003***	-0.003***	-0.003***	-0.003***	-0.003***	-0.003***
	(0.0002)	(0.0002)	(0.0002)	(0.0002)	(0.0002)	(0.0002)
Paired Band	1.162***	1.238***	1.077***	1.151***	1.226***	1.116***
	(0.081)	(0.081)	(0.080)	(0.079)	(0.081)	(0.080)
Frequencies above 2000MHz	-0.892***	-0.800***	-0.839***	-0.752***	-0.816***	-0.775***
	(0.225)	(0.223)	(0.221)	(0.218)	(0.223)	(0.218)
Frequencies between 1000 and 2000 MHz	-0.552***	-0.498***	-0.586***	-0.534***	-0.515***	-0.555***
	(0.167)	(0.165)	(0.163)	(0.162)	(0.166)	(0.162)
High Frequency Effect after MIMO	1.026***	0.900***	0.844***	0.725***	0.932***	0.752***
	(0.284)	(0.282)	(0.278)	(0.276)	(0.282)	(0.276)
Closed License	0.072	0.020	-0.065	-0.112	0.043	-0.093
	(0.261)	(0.258)	(0.255)	(0.253)	(0.258)	(0.253)
Spectral Efficiency per Site (bit/S/Hz/site)	-0.053***	-0.050***	-0.062***	-0.059***	-0.051***	-0.060***
	(0.008)	(0.008)	(0.008)	(0.008)	(0.008)	(0.008)
NASDAQ	0.001***	0.001***	0.001***	0.001***	0.001***	0.001***
	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)
Total Spectrum Offered in Auction	0.0001***	0.0001***	0.00004***	0.00004***	0.0001***	0.00004***
	(0.00000)	(0.00000)	(0.00000)	(0.00000)	(0.00000)	(0.00000)
Bidder-Specific Variables						
Bid Credit Used by DE (Dummy)	-0.298***		-0.343***			
	(0.031)		(0.031)			
Small Business Bid Credit (Dummy)		-0.378***		-0.420***	-0.342***	-0.389***
		(0.032)		(0.031)	(0.037)	(0.036)
Rural Provider Bid Credit (Dummy)		0.500***		0.433***	0.475***	0.416***
		(0.090)		(0.088)	(0.091)	(0.089)
Market-Specific Measures						
# of bidders for license			0.229***	0.222***		0.202***
			(0.024)	(0.024)		(0.032)
# of bidders for license, squared			-0.010***	-0.010***		-0.006**
			(0.002)	(0.002)		(0.003)
Incentive Auction Dummy & Interactions						
Incentive Auction (IA) (Dummy)	-1.659***	-1.832***	-1.772***	-1.943***	-1.760***	-1.580***
	(0.189)	(0.188)	(0.186)	(0.185)	(0.192)	(0.269)
Small Business Bid Credit * IA					-0.141*	-0.108
					(0.072)	(0.071)
# of bidders * IA						-0.044
						(0.054)
# of bidders sq * IA						-0.0004
						(0.004)
Constant	-15.416***	-15.741***	-15.013***	-15.323***	-15.776***	-15.230***
	(0.791)	(0.784)	(0.775)	(0.768)	(0.784)	(0.774)
Observations	4,223	4,223	4,219	4,219	4,223	4,219
R^2	0.823	0.826	0.831	0.834	0.827	0.835
Adjusted R^2	0.822	0.826	0.830	0.834	0.826	0.834
Residual Std. Error	0.828 (df = 4207)	0.819 (df = 4206)	0.809 (df = 4201)	0.801 (df = 4200)	0.819 (df = 4205)	0.800 (df = 4197)
F Statistic	1,301.837*** (df = 15; 4207)	1,251.685*** (df = 16; 4206)	1,214.008*** (df = 17; 4201)	1,175.282*** (df = 18; 4200)	1,179.058*** (df = 17; 4205)	1,010.434*** (df = 21; 4197)

Incentive Auction Dummy & Interactions: In all specifications, the coefficient on the Incentive Auction dummy is negative and statistically significant. While it is difficult to ascertain exactly why this is the case, it is clear that the Incentive Auction depressed auction outcomes. This is consistent with the observations from the prediction comparison, in which majority of predictions were greater than observed values.

We further consider an interaction between the Incentive Auction dummy and small business bidding credits. The coefficient for the *Small Business * IA* interaction in specification (17) is negative and statistically significant, which implies that small bidders in the Incentive Auction are associated with even lower prices than small bidders in previous auctions. While this is plausibly attributable to the Incentive Auction's structure, it could also be because the criteria for "small bidders" was relaxed right before Incentive Auction: the FCC had raised the maximum revenue standard from $40 million to $55 million for the 15% credit, and from $15 million to $20 million for the 25% credit (FCC, 2014; FCC, 2015b). As a result, many more bidders were eligible for credits compared to previous auctions. This may have depressed values, since small business bidder credits are empirically associated with lower license prices, as observed throughout this paper and in Connolly et al. (2017).

5. Conclusion

5.1 Limitations

Given the stark differences between the Incentive Auction and previous spectrum auctions, we acknowledge that certain methods used in this paper might be limited. Although we model valuation as a sum of forward auction clock prices and assignment phase bids, strategic and collusive behavior could have affected total clearing targets, and lowered bids placed in the forward clock auction. Furthermore, the methodology adopted by the FCC to calculate assignment phase payments does not exactly correspond to the definition of a "second-price" auction, which might affect the validity of our valuation metric.

Our GDP-weighted method of disaggregating assignment phase bids and payments also introduces additional assumptions that may bias these results. For example, there may have synergies between PEAs within a PEA group that created extra value in the assignment phase bid. Similarly, our models do not control for geographical complementarities due to a lack of data about each firm's existing spectrum holdings. As explored in the literature, this might be a significant driver of price above and beyond the sum of individual market traits (Ausubel et al., 1997; Moreton and Spiller, 1998; Fox and Bajari, 2013).

Additionally, a central component of the Incentive Auction is the interaction between the reverse and forward auction, which is determined by progress towards the final stage rule. While we did not make use of bid data from earlier stages in the auction, further studies could explore the impact of such an "endogenous" supply of licenses on auction outcomes.

5.2 Summary & Implications

In this paper, we take a multi-faceted approach towards studying the 2016 Incentive Auction. We consider the impact of designated entity bidding credits on forward auction clock prices, construct measures for true valuation, and evaluate the impact of the Incentive Auction's structure on headline winning bids in the context of previous spectrum auctions.

We study outcomes from the forward auction alone, and find that the inclusion of a "reserve" of licenses for only reserve-eligible bidders did not seem to have made a significant difference in clock price outcomes. This may either be attributed to the particular profile of participants in this auction (who were largely reserve-eligible), or may be an area for the FCC to refine in the future.

Other results confirm previous empirical findings on market and license traits. Similar to Connolly et al. (2017), we find that DE winning bidders (small businesses and rural entities) are associated with negative impacts on license valuations. Through our small/rural bidder composition measures, we find that higher proportions of small bidders, particularly those with 25% bidding credits, have negative price effects. In contrast, higher proportions of rural bidders have positive price effects, which we hypothesize may be the result of the concentration of rural bidders in rural markets. Even then, the bidder-specific rural provider dummy was negative and statistically significant, which suggests that rural bidders and small bidders alike have lower valuations of licenses as compared to regular bidders. As the first spectrum auction to include a bidding credit for rural providers, the results from the Incentive Auction could thus have important implications regarding the impact of rural credits in future spectrum auctions.

By analyzing outcomes using data from both the Incentive Auction and previous auctions, we find that license prices were lower in the Incentive Auction compared to other cellular service related auctions from 2007 to 2015. We expand Connolly et. al's (2017) model of spectrum valuation by including observations with larger bandwidth sizes. We believe this was one of the potential factors that diminished the accuracy of Connolly et al.'s (2017) out of sample predictions. Additionally, through interaction effects we find that small bidders in the Incentive Auction are associated with even lower prices than in previous auctions. This could be a result of the auction's unique mechanisms, or potentially a reflection of the recently loosened eligibility requirements for bid credits.

However, on the whole it is difficult to determine at this point whether these depressed license valuations are a result of the Incentive Auction's novel structure, or a significant difference in the types of participants. Although this particular issue is beyond the scope of this paper, it remains an important area for future research.

The first two-sided Incentive Auction successfully repurposed 84 MHz of spectrum to be put toward more efficient use as new technology emerges in the wireless communications space. Our findings that the auction resulted in lower license valuations relative to previous spectrum auctions may be important going forward as the FCC continues to refine the design of the Incentive Auction.

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APPENDIX A: Additional Procedural Details on the Incentive Auction

Reverse Auction

The Incentive Auction has been specially designed so as to allow for "repacking" – the process of moving existing channels to other parts of the frequency. Because of this, broadcasting stations have been offered varying bids and valuations depending on how much interference they will cause in the repacking process (those who will cause more interference will be offered higher bids, since it would greatly simplify the repacking process). They have also been offered different incentives depending on the type of repackaging they choose to be subject to: (a) going off-air entirely (this option also applies to broadcasters who wish to share a channel); (b) moving to Low-VHF; (c) moving to High-VHF; and (d) remaining in UHF. The entire process is aided by the use of an optimization software that figures out price offers based on the feasibility of each option for a given station.

Forward Auction

The forward auction operates through an ascending clock auction format. The clock price for each round represents the highest price a bidder can offer in a given round (i.e. they can offer any bid between the old and new clock prices). If the demand for a license exceeds the supply in any given round, then the clock price for the license will increase by a fixed percentage (bidding increments) in the next round. This prevents the possibility of excessive jump bids. If demand fails to meet supply during a round, then the next round's clock price will be set by adding the bidding increment to the price at which demand became equal to supply.[35] The rules of the Incentive Auction allow for this bidding increment to be set anywhere between 1% and 15%, and

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[35] This price might be an intra-round bid price, meaning that the bid price was not as high as the clock price, since that represents the highest possible bid.

the FCC set the initial increment at 5%. The flexible design of the bidding increments is meant to allow the auction to move at a reasonable pace, while at the same time ensuring that "price increases over a broad range of markets remain relatively balanced" (FCC, 2015b, para. 193).

Final Stage Rule

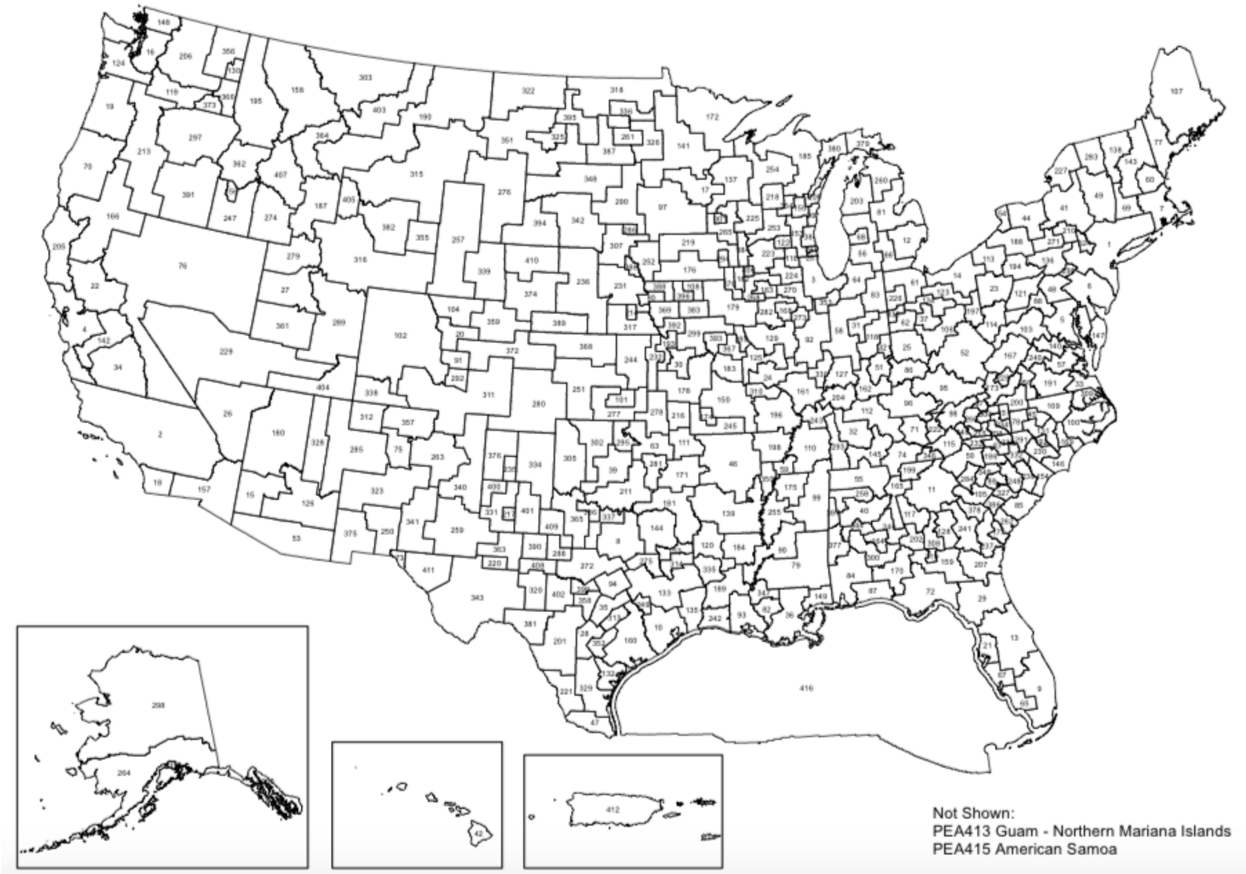
The *final stage rule* requires that the forward auction produce enough revenue to meet *competitive price level standard* and cover the costs of purchasing spectrum rights in the reverse auction, and associated expenses. The requirements to meet the "competitive price level standard" differ according to how much spectrum is cleared in the auction:

(a) If 70MHz or less is cleared, the average price for Category 1 licenses in high demand PEAs in the forward auction must meet or exceed $1.25 per MHz-pop;

(b) If more than 70MHz is cleared, the total proceeds of the forward auction must be greater than *$1.25 per MHz-pop x 70 MHz x the total number of pops for the high-demand Partial Economic Areas (PEAs) with at least one Category 1 block in the current stage*. This way, even if the average price per MHz-pop has not reached the benchmark price, the final stage rule may be met if the incentive auction repurposes a relatively large amount of spectrum. (FCC, 2017b)

APPENDIX B: Map of PEAs

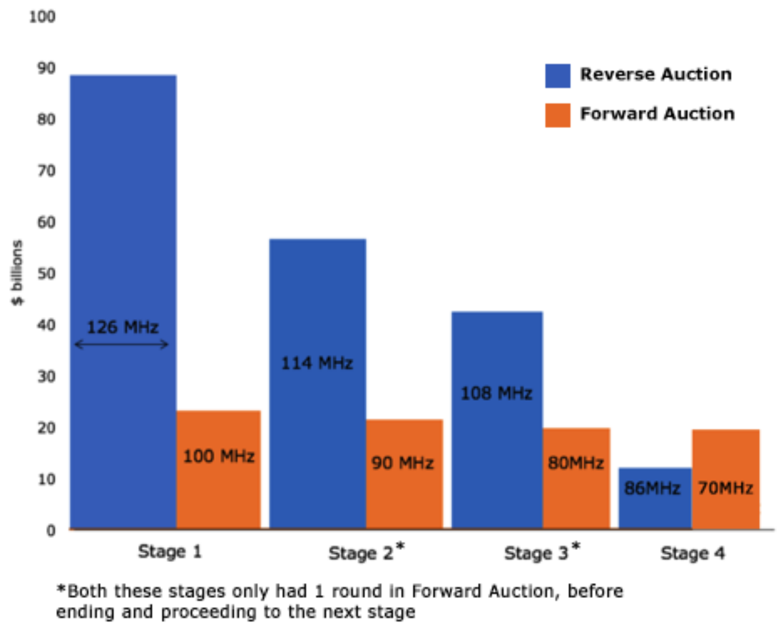
Figure B1: FCC Partial Economic Area (PEA) Boundaries (FCC, n.d.)



APPENDIX C: Outcomes of the 2016 Incentive Auction

Figure C1: Comparison of Reverse and Forward Auction Revenues By Stage

Adapted from Wallston (2017)



The 2016 Incentive Auction occurred over 4 stages (reverse-forward auction iterations). Stage 1 had 27 clock rounds, Stage 2 had 1 clock round, Stage 3 had 1 clock round, and Stage 4 had 58 clock rounds. The final stage rule was met in Stage 4 Round 2, at which point only C1 licenses remained in the auction (no licenses with higher impairment had been cleared in the reverse auction), and these C1 licenses were then split up into C1-R and C1-U licenses. None of the final C1 licenses had any impairments, and thus no impairment discounts were given.

Table C1: Summary of Costs and Revenue, by Stage

Stage	Reverse Auction Costs	Forward Auction Revenues
1	$86.4 bn	$23 bn
2	$54.6 bn	$21.5 bn
3	$40.3 bn	$19.7 bn
4	$10 bn	$19.8 bn

The auction resulted in $19.3 billion in net proceeds, $10.05 billion of which went to cover the clearing cost of the reverse auction. Revenues from rural businesses in the forward auction accounted for roughly 2.29% of the net proceeds, at $442.5 million, and revenues from small businesses accounted for 8.63%, at $1.67 billion.

Figure C2: Progress towards Final Stage Rule

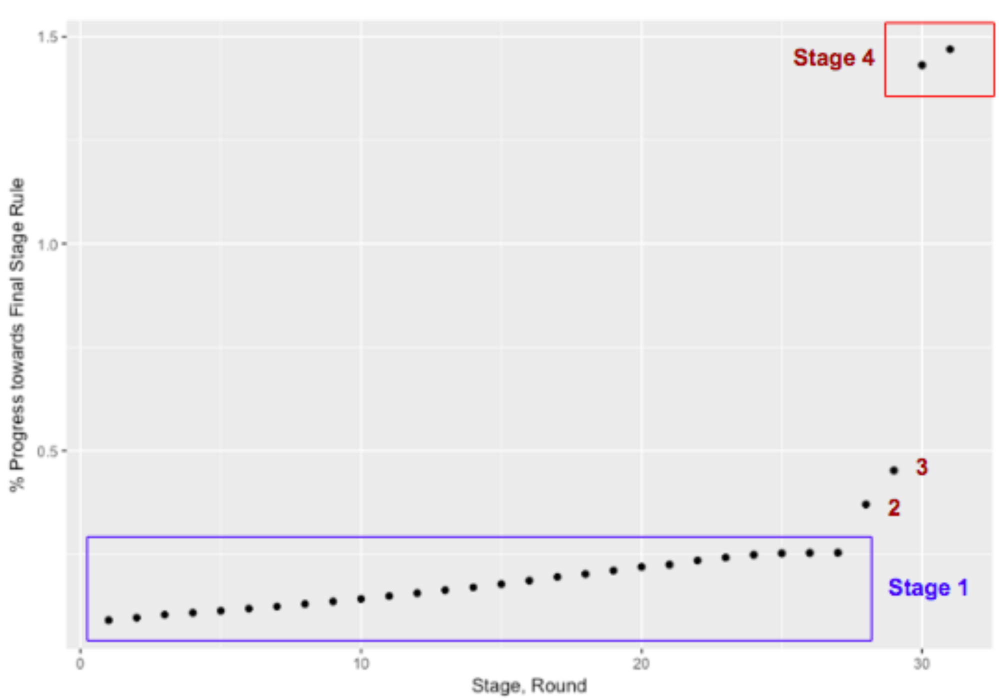


Figure C2 shows the progress of the auction towards the final stage rule, by individual rounds within a stage, up to Stage 4 Round 2 (at which point the final stage rule was met). The y-axis indicates the *progress* in percentages, which is calculated by simply dividing the *estimated net proceeds* by the *target net proceeds* in a given round. We see that progress in Stages 1, 2, and 3 were largely unsatisfactory, not even reaching 50% (0.5 on the y-axis).

During the first stage, which sought to clear 126 MHz of spectrum to be repackaged into 100 MHz of spectrum licenses to be sold (10 licenses per PEA), broadcasters asked for $86.4 billion in the reverse auction. However, the forward auction only garnered $23 billion in revenue, and hence the final stage rule was not met, pushing the auction into Stage 2 with a lower clearing target of 114 MHz (for 90 MHz of usable spectrum). By the time the auction reached Stage 4, the costs demanded by the broadcasters had fallen to around $10 billion.

In both stages 2 and 3, the forward auction concluded within one round. At stage 3, no bidders increased their bids, so the overall revenue from the forward auction decreased from Stage 2. In round 1 of stage 4, revenues from the forward auction exceeded clearing costs, but the second component of the final stage rule regarding a minimum price per MHz-pop of spectrum was not met, and the auction continued. In round 2 of stage 4, however, both components of the final stage rule were satisfied, clearing 86 MHz of spectrum including 70 MHz of licenses.

Reducing the clearing target made the repackaging process much easier, greatly reducing the prices being offered to relatively expensive broadcasters, and thus lowering the clearing costs needed to meet the final stage rule. This is because a smaller clearing target provided additional channels for television broadcasting (Leyton-Brown, Migrom & Segal, 2017). As some broadcasters exited the market and others accepted lower prices, the clearing costs demanded in the reverse auction fell sharply. Similarly, with a decrease in supply of licenses in the forward auction, average price per licence rises. Despite a lower quantity of licenses being sold, total revenue increased from stage 3 to stage 4.

APPENDIX D: Other Issues in the Incentive Auction

1. Designated Entities: Small & Rural Bidders

The next three tables summarize the types of bidders by bidding credit, the number of bidders at various stages of the auction, and the distribution of final licenses among the different types of bidders. These statistics clearly contrast trends in previous FCC auctions. Connolly et al. (2017) note that 49% of all cellular licenses since 1997 have actually been won by small bidders, and 44% of those licenses were won using small bidder credits.

Table D1: Number of Bidders, by Bidding Credit

Type of Bidder	**Credit Value**	**#**
Regular	None	14
Rural Provider	15%	28
Small Business	15%	3
Small Business	25%	17

Table D2: Composition of Bidders throughout Incentive Auction

	Regular Bidders	**Rural Providers**	**Small Businesses**	***Total Bidders***
Entire Auction	14	28	20	*62*
In Stage 4	13	27	18	*58*
Winning bidders	11	24	15	*50*

Table D3: Final Distribution of Licenses, by Bidder Type

	Regular	**Rural Providers**	**Small Businesses**	***Total***
C1-R Licenses	1036	91	96	*1223*
C1-U Licenses	1295	94	164	*1553*
Total	2331	185	260	*2776*

2. Big Winners

Given that the outcomes of the 2016 Incentive Auction, in terms of composition of winning bidders, seemed to differ a lot from previous spectrum auctions, we investigated the "biggest winners" of the auction - those who won the most number of licenses. More than half of all the licenses were bought by T-Mobile (1525 licenses, 55% of all licenses sold), with the next biggest winner being ParkerB.com Wireless (486 licenses, 17.5% of all licenses sold). T-Mobile, ParkerB.com Wireless and United States Cellular Corporation were also the highest spending bidders, accounting for $15.9 billion of the auction's $19.8 billion gross proceeds (80.3%).

T-Mobile: T-Mobile clearly dominated the auction, paying out almost $8 billion. According to news reports, it had earlier declared its intention to be aggressive in the Incentive Auction, and had been active in preparing the funds necessary for the process (Meyer, 2017). Their winnings in the Incentive Auction have now given them coverage over the entire US as well as Puerto Rico, allowing them to compete nationwide, and helping them catch up with Verizon and AT&T. The 600MHz licenses might also allow them to reach a higher level of competition, given that low-band spectrum improves in-building coverage and also travels further distances than mid or high band spectrum (T-Mobile, 2017; Kastrenakes, 2017).

ParkerB.com Wireless: Also known as Dish Network, ParkerB.com had previously acquired a substantial number of licenses in the FCC's recent auctions. However, unlike in previous auctions, they participated in the Incentive Auction without a designated entity status (and thus bidding credit).

Verizon & AT&T: Verizon, AT&T and Dish Network (ParkerB.com Wireless in the Incentive Auction) had accounted for 93% of the revenue in Auction 97 (AWS-3) (Meyer, 2015a). However, although Verizon was registered to take part in the Incentive Auction, it did not bid at all. Furthermore, while AT&T did participate in the auction, it won only 23 licenses.

3. Use of "Reserved" Spectrum

The Incentive Auction cleared 84MHz of total spectrum, including 70 MHz of usable spectrum (7 licenses in each PEA).[36] In this scenario, up to 3 licenses in each PEA could be marked for "reserve-eligible" bidders, and would operate under a separate clock price from the non-reserved licenses.

Table D4: Summary of Forward Auction Clock Prices, by category

Category	**Mean**	**Min**	**Max**	**S.D.**	**Median**
C1 Reserved	6,924,735	5,000	477,249,780	33,240,366	1,000,000
C1 Unreserved	6,994,803	5,000	477,249,780	33,377,964	1,000,000

On average, reserved licenses fetched lower clock prices and experienced less variation in the forward auction, although the minimum and the maximum are the same across both

[36] The other 14MHz was used as a 3MHz guard band and an 11 MHz duplex gap (FCC, 2016b).

categories. Although it might have been expected that the inclusion of a “reserve” could have helped “reserve-eligible” bidders by creating a separate round clock price that might settle at a lower value (relative to reserved licenses), it does not seem to have created a huge difference in reality.

Table D5: Number of Winning Bidders, by Type

Winning Bidders, by Type	**#**
All Winning Bidders	50
Reserve License Winning Bidders	40
Unreserved License Winning Bidders	45

In order to explain why the “reserve” was not effective, we looked at the composition of winning bidders by license types (Table D5). There were only 50 unique winning bidders across the entire auction, yet 40 of these bidders bought a reserve license in at least one PEA. As per the criteria for reserve eligibility, nationwide providers are only “reserve-eligible” in PEAs in which they do not already hold substantial interest.[37] T-Mobile, who was the biggest winner of the auction, emerging with 1525 licenses in 414 markets, was actually a reserve-eligible bidder in 392 of these markets. The presence of such “big bidders” who satisfied the different eligibility criteria of the reserve spectrum might thus explain why there is so little difference in the final clock prices across the two categories.

[37] Substantial interest as defined by holding less than 45 megahertz of below-1-GHz spectrum in a given PEA (FCC, 2016a, para. 100).

APPENDIX E - Description of Variables Used

Variable Name	Details
LICENSE-SPECIFIC CHARACTERISTICS	
License Bandwidth	Continuous variable, measured in MHz. We also include a measure for license bandwidth squared.
Paired Band	Dummy variable; 1 if a license has a paired uplink and downlink portion.
Frequency Range	Categorical variable for the location of the license on the spectrum; High (>2000 MHz); Middle (1000 - 2000 MHz); Low (<1000 MHz). The reference group is Low.
High Frequency effect after MIMO	Dummy variable; 1 if the license is in Middle or High frequency ranges (>1000MHz) and is sold after 2009, when Multiple-Input Multiple-Output (MIMO) technology was introduced. MIMO increased the spectral efficiency of high frequency licenses (Kerans et al., 2011).
License Frequency Block	Categorical variable for the specific frequency of a license won in the Incentive Auction: A, B, C, D, E, F, G. The reference group is G.
Closed License	Dummy variable; 1 if a license was sold in a closed auction that only designated entities could participate in.
Bidding Credit Used, Small Business Bid Credit, Rural Provider Bid Credit	Dummy variable. Depending on the specification, might be 1 for all bidders receiving a bidding credit, or may differentiate between small businesses (all auctions) and rural providers (only received bidding credit in Incentive Auction)
Number of Bidders	Continuous variable.
SMALL & RURAL BIDDER MEASURES (Incentive Auction Only)	
Presence of Small Business	(1) Dummy variable; 1 if at least one small business was bidding in the given market and license type; (2) Continuous variable from 0 to 1, measuring percentage of all bidders in the given market and license category that were small businesses
Presence of Rural Provider	Same as above, but for rural providers
Winning Small Business	(1) Dummy variable; 1 if at least one small business won a license in the given market and license type; (2) Continuous variable from 0 to 1, measuring percentage of all winning bidders in the given market and license category that were small businesses
Winning Rural Provider	Same as above, but for rural providers
AUCTION-LEVEL CHARACTERISTICS	
Total Spectrum Offered in Auction	Continuous variable, measured in MHz.
Auction 73 Block License with Open Access Requirement	Dummy variable; 1 for Auction 73 observations.

Incentive Auction	Dummy variable; 1 for Incentive Auction observations.
MARKET TRAITS	
Population Covered	Logged continuous variable.
Population Density	Logged continuous variable.
Real Median Income	Logged continuous variable, converted to 2000 dollars.
AGGREGATE TRAITS	
NASDAQ Index	Continuous variable for the closing value of the NASDAQ in the month the auction occured. Following Hazlett (2008), this measure reflects investor sentiment.
Spectral Efficiency per site	Continuous variable, measured in bit/S/Hz/site. Spectral efficiency is defined as the rate information can be transmitted over a given bandwidth in a specific communication system. This measure captures the greater efficiency of spectrum use over time through technological improvements.

APPENDIX F: Impact of DE on Forward Auction Clock Prices (with # of bidders)

	Dependent variable: Log Final Clock Price				
	(1)	(2)	(3)	(4)	(5)
Population (Logs)	1.104***	1.157***	1.134***	1.103***	1.124***
	(0.034)	(0.030)	(0.032)	(0.028)	(0.032)
Population Density (Logs)	0.011	0.062**	0.038	0.088***	0.043
	(0.028)	(0.026)	(0.027)	(0.025)	(0.027)
Real Median Income (Logs)	0.679***	0.870***	0.908***	0.755***	0.883***
	(0.153)	(0.139)	(0.143)	(0.130)	(0.143)
Reserved Type	-0.026	-0.070	-0.098**	-0.068	-0.097*
	(0.053)	(0.047)	(0.049)	(0.044)	(0.049)
Presence of Rural Provider (Dummy)		0.340***			
		(0.065)			
Presence of Small Business (Dummy)		-0.731***			
		(0.060)			
Winning Rural Provider (Dummy)			0.386***		
			(0.077)		
Winning Small Business (Dummy)			-0.544***		
			(0.058)		
% of bidders Rural				0.769***	
				(0.224)	
% of bidders Small				-2.600***	
				(0.171)	
% of winning bidders Rural					0.845***
					(0.177)
% of winning bidders Small					-1.226***
					(0.130)
# of bidders	0.066***	0.115***	0.071***	0.168***	0.069***
	(0.012)	(0.013)	(0.011)	(0.014)	(0.011)
Constant	-7.880***	-10.779***	-10.719***	-9.222***	-10.316***
	(1.624)	(1.484)	(1.525)	(1.387)	(1.525)
Observations	822	822	822	822	822
R^2	0.799	0.842	0.828	0.862	0.828
Adjusted R^2	0.798	0.841	0.827	0.861	0.826
Residual Std. Error	0.759 (df = 816)	0.674 (df = 814)	0.702 (df = 814)	0.630 (df = 814)	0.704 (df = 814)
F Statistic	647.809*** (df = 5; 816)	619.563*** (df = 7; 814)	561.715*** (df = 7; 814)	724.497*** (df = 7; 814)	558.472*** (df = 7; 814)

APPENDIX G: Baseline Valuation Model, with # of bidders

	Dependent variable: Log Valuations			
	(1)	(2)	(3)	(4)
Population (Logs)	1.037***	1.050***	1.022***	1.070***
	(0.026)	(0.027)	(0.022)	(0.024)
Population Density (Logs)	0.051**	0.061***	0.116***	0.092***
	(0.022)	(0.022)	(0.019)	(0.021)
Real Median Income (Logs)	0.591***	0.581***	0.574***	0.776***
	(0.119)	(0.121)	(0.101)	(0.109)
License Bandwidth	0.175***	0.186***	0.114***	0.144***
	(0.015)	(0.015)	(0.013)	(0.014)
License Bandwidth Squared	-0.004***	-0.004***	-0.002***	-0.003***
	(0.0003)	(0.0003)	(0.0003)	(0.0003)
Bidder-Specific Variables				
Small Business 15% Bid Credit (Dummy)	-0.245	-0.190	0.123	0.148
	(0.151)	(0.152)	(0.127)	(0.140)
Small Business 25% Bid Credit (Dummy)	-0.868***	-0.911***	-0.411***	-0.447***
	(0.061)	(0.063)	(0.055)	(0.063)
Rural Provider 15% Bid Credit (Dummy)	0.091	0.084	-0.262***	-0.332***
	(0.087)	(0.088)	(0.079)	(0.090)
Market-Specific Small/Rural Measures				
% of bidders Rural			0.702***	
			(0.194)	
% of bidders Small			-2.831***	
			(0.144)	
% of winning bidders Rural				1.326***
				(0.193)
% of winning bidders Small				-1.565***
				(0.129)
# of bidders	0.074***		0.178***	0.081***
	(0.009)		(0.010)	(0.009)
# of winning bidders		0.188***		
		(0.033)		
Frequency Block Controls				
Frequency Block A	0.123	0.170**	-0.035	-0.023
	(0.079)	(0.082)	(0.067)	(0.073)
Frequency Block B	0.359***	0.288**	0.205*	0.293**
	(0.134)	(0.137)	(0.112)	(0.122)
Frequency Block C	0.251	0.236	0.263*	0.241
	(0.188)	(0.190)	(0.157)	(0.172)
Frequency Block D	0.440**	0.367**	0.345**	0.416***
	(0.171)	(0.175)	(0.143)	(0.156)
Frequency Block E	0.513***	0.494***	0.250***	0.376***
	(0.101)	(0.102)	(0.085)	(0.092)
Frequency Block F	0.164	0.150	0.105	0.084
	(0.102)	(0.103)	(0.085)	(0.093)
Constant	-7.702***	-8.030***	-7.230***	-9.820***
	(1.257)	(1.273)	(1.080)	(1.161)
Observations	1,352	1,352	1,352	1,352
R^2	0.829	0.824	0.881	0.858
Adjusted R^2	0.827	0.822	0.880	0.856
Residual Std. Error	0.748 (df = 1336)	0.758 (df = 1336)	0.624 (df = 1334)	0.681 (df = 1334)
F Statistic	430.389*** (df = 15; 1336)	418.046*** (df = 15; 1336)	581.913*** (df = 17; 1334)	475.054*** (df = 17; 1334)

APPENDIX H: Modification of Connolly et. al (2017) models

The original model uses auction data from 2007 to 2015, and includes an infrastructure proxy (average download speeds) in each market. As we were unable to gather such data for the Incentive Auction, we modify models 3 and 4 to remove this variable. Even after removing the infrastructure proxy variable, the direction of the coefficients remain the same, and do not change by much. We believe that this verifies our method of using the modified models to make our predictions.

	Dependent variable: Log Real Headline Price (2000 dollars)	
	Model 3, Modified	Model 4, Modified
License Bandwidth	0.621***	0.567***
	(0.034)	(0.034)
License Bandwidth Squared	-0.018***	-0.016***
	(0.001)	(0.001)
Paired Dummy	0.275**	0.268**
	(0.107)	(0.106)
Frequencies above 2000 MHz	-0.379*	-0.471**
	(0.229)	(0.225)
Frequencies between 1000 and 2000 MHZ	-0.196	-0.261
	(0.164)	(0.162)
High Frequency Effect after MIMO	1.279***	1.192***
	(0.285)	(0.280)
Closed License	-0.091	-0.182
	(0.255)	(0.250)
Bid Credit Used in Winning Bid	-0.351***	-0.374***
	(0.037)	(0.037)
Population (Logs)	1.195***	1.180***
	(0.018)	(0.018)
Population Density (Logs)	0.100***	0.086***
	(0.014)	(0.014)
Real Median Income (Logs)	1.199***	1.091***
	(0.093)	(0.092)
Spectral Efficiency per Site (bit/S/Hz/site)	-0.067***	-0.072***
	(0.008)	(0.008)
NASDAQ	0.0004***	0.001***
	(0.0001)	(0.0001)
Total Spectrum Offered in Auction	0.0001***	0.00004***
	(0.00000)	(0.00000)
# of bidders for license		0.152***
		(0.032)
# of bidders for license squared		-0.004
		(0.003)
Constant	-19.947***	-18.936***
	(0.959)	(0.953)
Observations	2,871	2,867
R^2	0.844	0.850
Adjusted R^2	0.843	0.849
Residual Std. Error	0.805 (df = 2856)	0.791 (df = 2850)
F Statistic	1,103.020*** (df = 14; 2856)	1,006.310*** (df = 16; 2850)

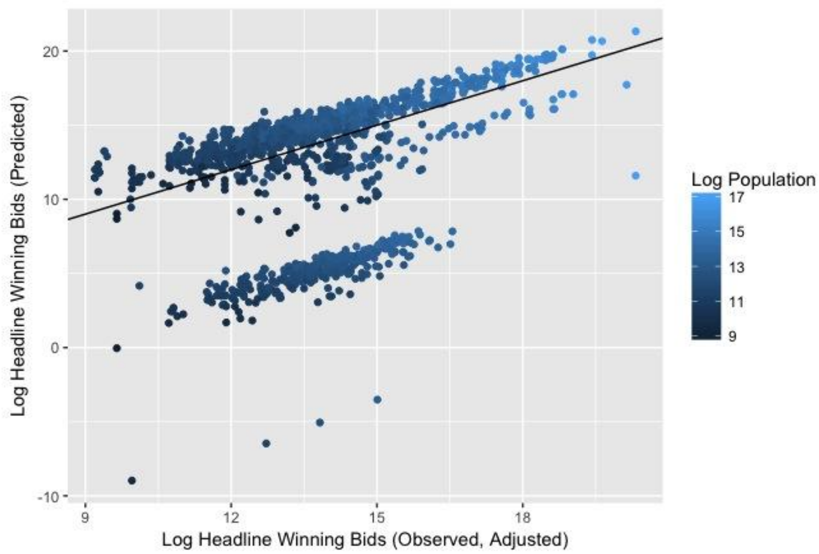
APPENDIX I

Combined Model with All Cellular Auctions, 1997 – 2017, including Incentive Auction

	Dependent variable: Log Real Headline Price (2000 dollars)					
	(1)	(2)	(3)	(4)	(5)	(6)
Population (Logs)	1.218***	1.217***	1.145***	1.145***	1.219***	1.149***
	(0.012)	(0.012)	(0.012)	(0.011)	(0.012)	(0.011)
Population Density (Logs)	0.008	0.013	0.011	0.015	0.013	0.016
	(0.011)	(0.011)	(0.010)	(0.010)	(0.011)	(0.010)
Real Median Income (Logs)	0.899***	0.910***	0.793***	0.803***	0.910***	0.803***
	(0.068)	(0.068)	(0.062)	(0.062)	(0.068)	(0.062)
License Bandwidth	0.172***	0.166***	0.221***	0.216***	0.167***	0.229***
	(0.008)	(0.008)	(0.008)	(0.008)	(0.008)	(0.008)
License Bandwidth Squared	-0.003***	-0.003***	-0.004***	-0.004***	-0.003***	-0.004***
	(0.0002)	(0.0002)	(0.0002)	(0.0002)	(0.0002)	(0.0002)
Paired Band	1.399***	1.431***	0.898***	0.927***	1.423***	0.862***
	(0.089)	(0.089)	(0.082)	(0.082)	(0.089)	(0.082)
Frequencies above 2000MHz	-1.979***	-1.974***	-1.439***	-1.439***	-1.970***	-1.419***
	(0.062)	(0.062)	(0.059)	(0.059)	(0.062)	(0.058)
Frequencies between 1000 and 2000 MHz	0.115***	0.103***	-0.085**	-0.094***	0.108***	-0.105***
	(0.037)	(0.037)	(0.035)	(0.035)	(0.037)	(0.035)
High Frequency Effect after MIMO	2.258***	2.203***	1.704***	1.662***	2.222***	1.673***
	(0.124)	(0.123)	(0.114)	(0.114)	(0.124)	(0.114)
Closed License	-0.228***	-0.209***	-0.047	-0.032	-0.217***	-0.029
	(0.046)	(0.046)	(0.042)	(0.042)	(0.046)	(0.042)
Auction 73 C Block Licenses	-0.603	-0.610*	-0.415	-0.421	-0.604*	-0.438
	(0.367)	(0.366)	(0.336)	(0.335)	(0.366)	(0.334)
Spectral Efficiency per Site (bit/S/Hz/site)	-0.096***	-0.093***	-0.063***	-0.061***	-0.094***	-0.059***
	(0.005)	(0.005)	(0.004)	(0.004)	(0.005)	(0.004)
NASDAQ	0.001***	0.001***	0.001***	0.001***	0.001***	0.001***
	(0.00003)	(0.00003)	(0.00003)	(0.00003)	(0.00003)	(0.00003)
Total Spectrum Offered in Auction	0.0001***	0.0001***	0.00004***	0.00004***	0.0001***	0.00004***
	(0.00000)	(0.00000)	(0.00000)	(0.00000)	(0.00000)	(0.00000)
Bidder-Specific Variables						
Bid Credit Used by DE (Dummy)	-0.466***		-0.438***			
	(0.026)		(0.024)			
Small Business Bid Credit (Dummy)		-0.500***		-0.466***	-0.481***	-0.442***
		(0.026)		(0.024)	(0.028)	(0.025)
Rural Provider Bid Credit (Dummy)		0.326***		0.215**	0.293***	0.222**
		(0.110)		(0.101)	(0.112)	(0.102)
Market-Specific Measures						
# of bidders for license			0.457***	0.452***		0.455***
			(0.015)	(0.015)		(0.017)
# of bidders for license, squared			-0.022***	-0.021***		-0.020***
			(0.001)	(0.001)		(0.001)
Incentive Auction Dummy & Interactions						
Incentive Auction (IA) (Dummy)	-1.678***	-1.809***	-1.654***	-1.767***	-1.742***	-0.272
	(0.128)	(0.129)	(0.119)	(0.120)	(0.133)	(0.233)
Small Business Bid Credit * IA					-0.160*	-0.115
					(0.082)	(0.075)
# of bidders * IA						-0.324***
						(0.053)
# of bidders sq * IA						0.015***
						(0.003)
Constant	-16.886***	-16.970***	-15.176***	-15.251***	-16.999***	-15.323***
	(0.693)	(0.691)	(0.637)	(0.635)	(0.691)	(0.633)
Observations	8,486	8,486	8,461	8,461	8,486	8,461
R^2	0.769	0.770	0.806	0.807	0.770	0.809
Adjusted R^2	0.768	0.770	0.806	0.807	0.770	0.809
Residual Std. Error	1.020 (df = 8469)	1.017 (df = 8468)	0.934 (df = 8442)	0.931 (df = 8441)	1.017 (df = 8467)	0.927 (df = 8438)
F Statistic	1,760.269*** (df = 16; 8469)	1,670.369*** (df = 17; 8468)	1,951.280*** (df = 18; 8442)	1,860.326*** (df = 19; 8441)	1,578.290*** (df = 18; 8467)	1,625.328*** (df = 22; 8438)

APPENDIX J

Figure J1: Model 3 (Modified) Prediction Plot, by Population



In Figure J1, data points further upward and rightward (i.e. higher license prices) become progressively lighter (i.e. larger populations), indicating that there is a clear positive relationship between populations and license prices. However, this relationship holds equally in both clusters, suggesting that the population size does not impact whether Model 3 (modified) overpredicts or underpredicts the observed (adjusted) values.

Figure J2: Model 3 (Modified) Prediction Plot, by Population

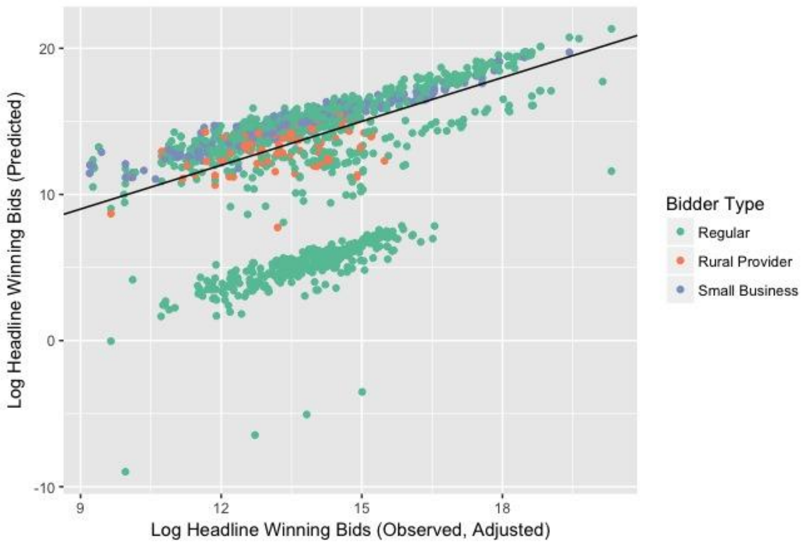


Figure J2 illustrates that the only observations that tend to be underpredicted are regular bidders (those without bidding credits). This might suggest that differences in outcomes might be a result of the particular profile of non-DE bidders who participated in the auction.[38] This led us to consider T-Mobile as a potential source of the clustering.

[38] See Appendix D.2 on the lack of participation of typical big bidders like Verizon and AT&T.