Market Design and the FCC Incentive Auction*

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Abstract

Market-based mechanisms for the allocation of spectrum licenses have been a prominent feature of the telecommunications landscape for more than two decades. Generally, spectrum auctions have taken the spectrum's use as given and have sought to allocate licenses efficiently. In March 2017, the FCC completed the Incentive Auction, the first-ever auction that incorporated voluntary clearing directly into the allocation mechanism. As such, it is the most prominent auction to date that has sought to let the market determine not only who uses the spectrum but how it is used. This article reviews the design and assesses the outcome of the FCC Incentive Auction.

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1. Introduction

Market-based mechanisms for the allocation of spectrum licenses have been a prominent feature of the telecommunications landscape for more than two decades. Federal Communications Commission (FCC) Auction #1 (the Nationwide Narrowband Auction) of July 1994 and FCC Auction #4 (the Broadband PCS A and B Block Auction) of December 1994 – March 1995 were pioneering United States efforts, while the UMTS/IMT-2000 Auctions in the UK (March – April 2000) and Germany (July – August 2000) were especially memorable for the stunningly high prices paid for 3G licenses.[1]

However, spectrum is never "new" and, typically, some incumbent party has been using a given swath of spectrum before it is auctioned as a spectrum license. Current practice is generally to make termination of the prior use of the spectrum a mandatory part of the allocation process, through the issuance of regulations (and sometimes with payment of some amount of compensation to the incumbent user). In recent years, economists have sought to integrate the clearing of incumbent uses of the spectrum into the auction process. Integrating voluntary clearing into spectrum auctions offers at least two potential advantages over current practice. First, to the extent that the cleared incumbents are the "winners" of an auction process, they may be incentivized to terminate their prior use in an expeditious way, instead of filing lawsuits or otherwise delaying the clearing. Second, by utilizing such a process, the policymaker can be confident that the repurposing of spectrum among uses and users is creating social surplus—and indeed the amount of repurposing can be made an endogenous part of the process.

More generally, traditional spectrum auctions have taken the spectrum's use as given and have merely sought to allocate licenses efficiently. In recent years, economists have sought the more ambitious objective of letting the market determine not only who uses the spectrum but *how* it is used. Integrating the clearing of incumbent uses of the spectrum into the auction mechanism may be viewed as a special case of this more ambitious agenda.

Bidding in the first-ever auction that incorporated voluntary clearing began on March 29, 2016 and concluded on March 30, 2017. Dubbed the FCC "Incentive Auction", its objective was to repurpose spectrum from television broadcasting to mobile broadband. The auction was successful in its objective, repurposing 84 MHz of low-band spectrum, including 70 MHz of licensed spectrum and 14 MHz for unlicensed use.

This article seeks to examine the FCC Incentive Auction from a market design perspective. In turn, we will review and assess the effectiveness of the meta-design of the auction, followed by looking in detail at particular facets of the reverse auction and the forward auction.[2]

At the outset, it should be observed that spectrum auctions are often put forward as a "poster child" for market design. While allocating spectrum via auction undoubtedly benefits government revenues, there has always been ambiguity as to whether previous auctions were successful in creating and maximizing social surplus. However, the FCC Incentive Auction presents a particularly strong case for efficiency gain:

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[1] Accounts and analyses of some of the early spectrum auctions are provided in McMillan (1994), Cramton (1995), McAfee and McMillan (1996), Jehiel and Moldovanu (2001), Binmore and Klemperer (2002) and Milgrom (2004).

[2] Other analyses relating to the FCC Incentive Auction include Loertscher, Marx and Wilkening (2015), Doraszelski, Seim, Sinkinson and Wang (2016), Milgrom and Segal (2017) and Milgrom (2017).

the new (mobile broadband) users revealed their values to be at least $19.3 billion, while the prior (television broadcasting) users revealed their costs to be at most $10 billion. Moreover, the holdout problem among broadcasters (described in the next section) appears to be insurmountable in the absence of an incentive-auction-like mechanism, making it unlikely that the repurposing of spectrum would have proceeded without it. In our view, it provides a compelling case study of market design improving social welfare.

The account that we provide has all the advantages and disadvantages of being an insider account. Larry Ausubel was a member of the design team and an author of the key design documents.[3] Christina Aperjis participated in many of the design decisions, was an author of many of the technical appendices to the FCC's public notices, and spent entirely too much of 2016–2017 in the FCC auction war room. Oleg Baranov also participated in the design of the assignment phase. And Power Auctions LLC, our company affiliation, was hired by the FCC to do the software implementation of the Incentive Auction.

The article is structured as follows. Section 2 reviews the foundations of the Incentive Auction. Section 3 provides a simplified model of the Incentive Auction. Section 4 describes some practical details of the auction process necessitated by the real world being messier than the simplified model. Section 5 assesses the overall performance of the auction. Section 6 explores particular facets of the reverse auction. Section 7 examines the clock phase of the forward auction. Section 8 identifies some interesting features of the assignment phase of the forward auction. Finally, Section 9 concludes.

2. Foundations of the Incentive Auction

Any discussion of an enterprise as complex as the Incentive Auction runs the risk of getting lost in the details of the auction mechanics and losing focus on the larger picture. In hopes of mitigating this risk, we begin our discussion by reviewing some of the foundations of the Incentive Auction.

2.1 Repurposing Spectrum

The objective of the Incentive Auction was to provide a practical market-based mechanism for repurposing some of the US radio communications spectrum below 698 MHz to mobile broadband, which most industry observers believed would be a higher valued use for the spectrum than its existing use for over-the-air television broadcasting. The reason for this belief was a combination of two trends. First, for many years, there had appeared to be a "spectrum shortage" for mobile telephony. While various other spectrum bands had been auctioned in recent years, data traffic driven by the success and ubiquity of the iPhone and other smartphones had grown exponentially for a decade. Second, spectrum utilization by traditional over-the-air television stations had long been in decline in the US. Not only were television stations apparently declining in popularity, but the vast majority of television viewers were receiving their signals by means other than "over-the-air". Ratings provider Nielsen Company reported that, in the first quarter of 2017, just 13% of American television households received their signal by "Broadcast Only," while 82% received their signal by "Cable Plus" (i.e., wired cable, telco or

[3] Milgrom, P., L. Ausubel, J. Levin and I. Segal (2012), "Incentive Auction Rules Option and Discussion," Appendix C to *Expanding the Economic and Innovation Opportunities of Spectrum Through Incentive Auctions*, Notice of Proposed Rulemaking, Docket No. 12-268, 27 FCC Rcd 12357 (2012), https://apps.fcc.gov/edocs_public/attachmatch/FCC-12-118A2.pdf, and Milgrom, P., L. Ausubel, J. Levin and I. Segal (2013), "Auctionomics/Power Auctions Option for Forward Auction," Supplement to Appendix C, https://ecfsapi.fcc.gov/file/7022116356.pdf.

satellite) and 5% received their content by "Broadband Only." [4] Nonetheless, allocation of the spectrum below 698 MHz for television precluded its efficient use for mobile broadband.

2.2 "Repacking" and the Holdout Problem

While the economic rationale for repurposing spectrum is strong, repurposing did not necessarily look like a fertile area for auctions. The reason is that auctions generally require competition to work effectively, while more than 2,000 television licensees each held unique rights to specific frequencies and locations. This created a complex and overlapping set of encumbrances to using the spectrum for mobile broadband. Given current mobile broadband and television broadcast technologies, entire swaths of spectrum would need to be cleared of broadcasting in order to be used for broadband.

This would give rise to an extremely ugly holdout problem. For example, to clear the spectrum that will ultimately be repurposed by the Incentive Auction would require the relinquishment or relocation of all of the stations using channels 38 – 51: for example, in a given market, there might be stations using channels 39, 40, 44, 45, 47, 48, 49 and 50. Thus, a fully "voluntary" process to repurpose the spectrum could require the unanimous agreement of eight or more separate owners, restricting attention to one local market. Once we consider that the same agreement would also be required in other key markets throughout the country, we might literally require unanimity among hundreds of broadcast licensees nationwide. Each of these licensees could then have the strategic incentive to demand a very high price for its spectrum rights.

A similar holdout problem arises in real property, in the assembly of large parcels of land for development. The approach taken to assemble the land required to build highways is known as "eminent domain": the government requires private landowners to relinquish their land in return for payment of fair market value. Such an approach, as well as the somewhat milder approach of allowing the broadcast licenses to expire at the end of their 10-year terms (instead of the fairly automatic renewal that they currently receive in the United States), was rejected by policymakers. Any market-based mechanism seemed unattainable.

The key insight, proposed in the *National Broadband Plan* (2010) and credited to the FCC's Evan Kwerel, is that there is a reasonably unobtrusive way to create competition for what would otherwise be unique items. Suppose that it is politically unacceptable to cancel the license of the broadcaster on channel 48, but that it is politically acceptable to require this broadcaster to relocate to channel 24. Then, in the above example, it might be sufficient to gain the approval of the stations on channels 20, 22, 24, 33, 45, 47, 49 and 50—with the intention that the stations on channels 39, 40, 44 and 48 would be relocated to channels 20, 22, 24 and 33.[5]

Under this methodology, which was authorized by Congress in the Middle Class Tax Relief and Job Creation Act of 2012, the FCC would conduct a reverse auction for as many channels as were needed to be relinquished in each market. The repurposing process would not be entirely voluntary—participation in the so-called "repacking" process would be obligatory. Nonetheless, if the government provides each relocating station with a new channel that reaches the same viewers as the old channel and if the government compensates them for the tangible costs of moving their frequencies, then no station is

[4] Nielsen Company, *The Nielsen Total Audience Report*, Q1 2017, Table 7.

[5] Federal Communications Commission (2010), p. 81.

harmed by the arrangement. By individual rationality, the "winners" in the auction (who choose to relinquish) are made better off, while the "losers" in the auction (who may be relocated) are left indifferent. In particular, there is no legitimate issue of uncompensated goodwill, since the station involuntarily moved from channel 48 to 24 might already be known as "channel 7"; referring to stations by their "virtual channel" numbers has been prevalent since the time of the digital transition (when many stations were moved from their historic analog channels).

2.3 Related Methodologies and Attempts

While the Incentive Auction is in major respects the first time that a voluntary clearing process has been incorporated directly into the market-based mechanism—and one of the few instances in which an auction has been applied to determine the use of spectrum (as opposed to merely determine its allocation)—it is by no means the first time that it was suggested. Kwerel and Williams (2002) proposed the concept of using a voluntary two-sided auction to repurpose spectrum. All licenses would eventually be liberalized to flexible use, but incumbent licensees would be incentivized to participate in the auction by liberalizing their licenses sooner than the licenses of non-participants (and by allowing them to keep the proceeds from the sale of their spectrum). Earlier, Kwerel and Williams (1992) had argued that spectrum was misallocated between UHF television and mobile wireless services. They proposed that one voluntary reallocation from television to mobile should be permitted in each local television market and they suggested that a voluntary reallocation approach could be applied usefully elsewhere in spectrum.

Hazlett (2017) proposed an alternative approach to repurposing broadcast spectrum. He advocated that the FCC instead auction "overlay licenses", which grant flexible use of the broadcast spectrum, subject to respecting the existing rights of the broadcast licensees. To the extent that the holders of the overlay licenses could acquire (and extinguish) the corresponding broadcast licenses, they would gain the right to use the broadcast spectrum for mobile broadband. Thus, it created incentives for the parties to negotiate private deals to realize the gains associated with repurposing. At the same time, Hazlett's proposal requires heroic faith in the ability of Coasean bargaining to reach a successful conclusion under incomplete information and with large numbers of parties.

Spectrum Exchange, a private venture organized in 1999 by Professors Peter Cramton, Larry Ausubel and Paul Milgrom, in partnership with the investment bank Allen & Company, attempted to establish a voluntary mechanism for the early repurposing of the upper 700 MHz spectrum. The FCC had planned to auction upper 700 MHz licenses in the early 2000s. In the initial years, these would effectively be overlay licenses, since approximately 100 analog television stations still operated in these frequencies; then, when the transition to digital television was completed, these stations would stop broadcasting in analog and the mobile spectrum licenses would become unencumbered. Spectrum Exchange attempted to establish a mechanism whereby the analog television stations would relinquish their licenses early, so that the 700 MHz spectrum would be usable sooner. However, the venture was shut down when Congress instructed the FCC to delay the upper 700 MHz auction by several years.

Past spectrum auctions have generally taken the use of the spectrum as given, so that the auction focuses solely on the allocation of spectrum licenses. However, in a couple of instances, regulators have attempted to incorporate usage decisions into the auction mechanism, so that the market would determine not only who gets to use the spectrum but also *how* the spectrum is used. The eventual 700 MHz auction (FCC Auction 73, conducted in the first quarter of 2008) included the provision that the C block would be subject to "open access" requirements, provided that an aggregate reserve price of $4.64 billion was met. In the actual auction, Google, which apparently valued the open access requirements, entered bids for the C block until the C block's reserve price was met and then stopped bidding. As a result, the requirements were triggered, but Google did not win any licenses (Brusco, Lopomo and Marx, 2009).

The initial design in 2007 for the 2.6 GHz UK auction included an endogenous band plan: any pair of blocks (5 MHz each) out of 38 total blocks offered in the auction would be available as either paired blocks (suitable for FDD technology) or as unpaired blocks (suitable for TDD technology).[6] During the auction, bidders would specify the quantity of paired and unpaired blocks that they wished to acquire, and then the auction would simultaneously determine the value-maximizing band plan and the winning allocation. The need for such a `technology-neutral' auction was important to the regulator Ofcom since, at the time, it was unclear which one of two competing technologies would generate more value (Cramton, 2013). The award of 2.6 GHz spectrum was delayed by a number of years and was eventually included as part of the UK 4G Auction held in 2013. By this time, the FDD technology had won out and Ofcom decided to employ the paired band plan. However, the auction did include an endogenous choice between a single high-powered user or multiple low-powered users for several 2x5 MHz blocks in the 2.6 GHz band. With the high-power use, the winner of the block would have exclusive rights for usage. With the low-power use, up to 10 winners would be allowed to share the same frequencies in different locations (Ausubel & Baranov, 2017).

2.4 Clock Auctions

The traditional auction format used for spectrum is the simultaneous multiple-round ascending (SMRA) auction. All spectrum licenses are auctioned simultaneously; every license in the auction is treated as a unique item that receives a separate bid. In each round, bidders have the opportunity to outbid their opponents by bidding at least one minimum bid increment higher than the standing high bidder for a license. The auction concludes when a round elapses with no new bids submitted by any bidder.

However, a somewhat newer innovation, the *clock auction*, offers a number of advantages over the traditional SMRA. In a clock auction, the auctioneer announces the price in each round and bidders respond with a quantity; this reduces to a bid of "in" or "out" for a single item. A clock auction format combines well with offering "generic" lots of spectrum. That is, instead of offering "New York Block A", "New York Block B", … , "New York Block G", the seller offers seven generic New York blocks. In the main phase of the auction, a bidder merely indicates the quantity of generic blocks that it desires in each region. This is followed by an assignment phase in which additional bid submissions determine the mapping from generic blocks to physical frequencies. The advantages of a clock auction for generic spectrum followed by an assignment stage, over the SMRA, include the following:

- Auctions run much quicker;
- Bidding is made strategically simpler; sometimes, truthful bidding may be a dominant strategy;
- Substitution is made easier, through the use of bids for quantities;
- Various strategic manipulations involving the fragmentation of spectrum are rendered infeasible; and
- It is easier to incorporate set-asides and other aspects of competition policy into the auction.

[6] FDD stands for 'frequency division duplex' and TDD stands for 'time division duplex'.

The clock auction format has been used frequently for energy and resource auctions since 2001, but has only occasionally been used for spectrum. As we shall see, both the forward and reverse auctions of the Incentive Auction utilized a clock format.

3. A Simple Model of an Incentive Auction with National Licenses

In this section, we provide a rather simplified model of the Incentive Auction. There are only national licenses, eliminating much of the complexity of the real auction. This facilitates explaining how each of the reverse and forward auctions operates, showing how the two parts of the auction fit together, and discussing some of the basic design issues and imperatives raised.

3.1 Procurement of stations without repacking

There are m incumbent television stations located within the spectrum band that is being repurposed (e.g., channels 38 – 51). Each station (i = 1, … , m) has a private cost, c_i, that is drawn independently from $[0, \infty)$ according to the commonly-known distribution function F_i. It is assumed that the spectrum can be repurposed only if all m incumbent stations voluntarily agree to relinquish their licenses.

As is well understood from Rob (1989) and Mailath and Postlewaite (1990), efficient agreement can become problematic when unanimity is required. In particular, as the number m of agents increases, the probability of an affirmative efficient decision goes to zero. They also provide an example in which it is common knowledge that an affirmative decision is efficient and yet the probability of such a decision goes to zero.

3.2 A reverse auction with repacking

Now consider the repacking protocol of the *National Broadband Plan* (2010) that is attributed to Evan Kwerel. There are m incumbent television stations located within the spectrum band that is being repurposed (e.g., channels 38 – 51), but a total of $n > m$ television stations in the UHF band overall (e.g., channels 14 – 51). Each station (i = 1, … , n) has a private cost, c_i, that is drawn independently from $[0, \infty)$ according to the commonly-known distribution function F_i. It is assumed that the spectrum can be repurposed so long as any m of the n incumbent stations in the UHF band voluntarily agree to relinquish their licenses; to the extent that any of the remaining $(n – m)$ stations are located above channel 37, they can be relocated to a lower channel that is being vacated by another station.

It is well understood that efficient clearing can now be accomplished via an auction. Each of the n stations can bid in a descending clock auction; the price clock stops at the first price p at which the aggregate supply drops to m items. The equilibrium with truthful bidding accomplishes efficient clearing at minimum expected cost; the final price p is expected to equal the $(m + 1)^{st}$ lowest clearing cost of any station. Furthermore, the marginal cost of clearing the m^{th} station is an increasing function of m.

3.3 A forward auction

There are N wireless broadband operators who would have value for one of the M blocks of mobile spectrum that would be created. Each operator (j = 1, … , N) has a private value, v_j, that is drawn independently from $[0, \infty)$ according to the commonly-known distribution function G_j.

It is well understood that efficient allocation can be accomplished via an auction. Each of the N operators can bid in an ascending clock auction; the price clock stops at the first price q at which the aggregate demand drops to M items. The equilibrium with truthful bidding accomplishes efficient allocation of the repurposed spectrum; the final price q is expected to equal the $(M + 1)^{st}$ highest value of any operator. Moreover, the marginal value of the M^{th} spectrum block is a decreasing function of M.

3.4 Establishing a clearing target

A key objective of the Incentive Auction was to determine the optimal level of spectrum to repurpose from television broadcasting to mobile broadband. Given the above structure of reverse auction and forward auction, one could conduct the auction in stages. Each *stage k* was associated with a particular clearing target, which represents a number m_k of television channels to be cleared and an associated number M_k of broadband spectrum blocks that would be created. In each successive stage, we simultaneously reduce the number of channels to be cleared and the number of spectrum blocks to be offered.

For simplicity, we will assume (counterfactually) that each television channel and each broadband spectrum block require the same quantity of spectrum, so that $m_k = M_k$. With this simplification, there is no need to normalize the reverse auction price p_k and the forward auction price q_k—and there is no need to concern ourselves with the integer problem that sometimes requires us to clear two or more additional television channels in order to create one more broadband block.

The Incentive Auction would begin with stage 1. First, the reverse auction could be run until a price p_1 was reached at which m_1 stations were willing to relinquish their licenses. Then, the forward auction could be run until a price q_1 was reached at which the resulting m_1 (= M_1) spectrum blocks would be efficiently sold. As argued above, p_1 represents the marginal cost of clearing one additional station and q_1 represents the marginal value of selling one additional spectrum block, so a comparison tells us whether clearing one more station and selling one more block improves efficiency. At the same time, a comparison of the clearing cost $m_1 p_1$ with the sales revenues $m_1 q_1$ tells us whether the mechanism is budget balanced. If it turned out that $q_1 \geq p_1$, then the mechanism is budget balanced at a clearing target of m_1; in addition, we would actually have preferred to clear $(m_1 + 1)$ blocks, so we would clearly not want to proceed to a smaller clearing target. Thus, if $q_1 \geq p_1$, we would deem stage 1 to be the final stage. In fact, we would know that this was the final stage at the moment that the ascending price clock reached p_1 (even before we knew the ultimate clearing price q_1), so we could deem that the *final stage rule* is triggered if and when a price of p_1 is reached in the forward auction. However, if $q_1 < p_1$, then the Incentive Auction would not satisfy the statutory requirement of budget balancedness.

In this event, we would proceed to stage 2, in which m_2 (< m_1) stations are cleared and M_2 (< M_1) spectrum blocks are sold. Again, we will simplify matters by assuming that $m_2 = M_2$. The reverse auction, whose descending price clock stood at p_1, could be resumed with only the stations that were still in the auction at the end of stage 1. The reverse auction is then continued until a clearing price $p_2 \leq p_1$ is reached at which m_2 stations are willing to clear. Then the forward auction, whose ascending price clock stood at q_1, could be resumed with only the mobile operators that were still in the auction at the end of stage 1. The forward auction is then continued and if the ascending clock reaches a price of p_2, then the final stage rule is deemed to be triggered in stage 2. However, if stage 2 of the forward auction ended at $q_2 < p_2$, then the Incentive Auction would again not satisfy the statutory requirement of budget balancedness, and we would proceed to stage 3, etc.

4. Practical Details of the Incentive Auction Design

As discussed above, the Incentive Auction comprised two separate but interdependent auctions: a reverse auction, where television broadcasters bid to relinquish their spectrum usage rights, and a forward auction, where wireless operators bid to acquire spectrum. In this section, we provide some details about the design that go beyond the model of Section 3.

4.1 Reverse auction design

A major complication, compared to the reverse auction for the simple model described in Section 3.2, is that in real life stations are not symmetric. Section 3.2 assumes that the spectrum can be repurposed so long as any *m* of the *n* incumbent stations in the UHF band voluntarily agree to relinquish their licenses. However, different stations have different interference constraints. As a result, the amount of spectrum that can be repurposed depends on *which* stations voluntarily agree to relinquish their licenses (not only on the number of such stations).

Another aspect of reality that is not accounted for in Section 3.2 is that the TV band consists of three separate bands: Low-VHF, High-VHF and UHF. In order to maximize the amount of cleared spectrum, the FCC allowed VHF stations to participate in the auction (in addition to UHF stations) and allowed both UHF stations and High-VHF stations to bid to move to a lower band. Then, there are multiple ways to clear a UHF channel. For instance, to clear channel 42 (a UHF channel) the FCC could pay stations that are currently on channel 42 to go off-air. Alternatively, the FCC could pay stations on channel 42 to move to channel 8 (which is a High-VHF channel) and then pay any High-VHF stations interfering with the UHF stations moved to channel 8 to go off-air.

The FCC used a descending clock auction format that accounts for the real life complications described above. This format has several advantages compared to a sealed-bid format. First, the clock format preserves the privacy of winning stations, because a station does not need to reveal the minimum amount it is willing to accept while it continues bidding in the auction. Instead, in every round, a bidder just has to decide whether it is willing to accept the price offered in that round (see Rothkopf, Teisberg and Kahn, 1990, and Ausubel, 2004). Second, a clock format avoids the "politically embarrassing newspaper headlines" when the amount of the winning bid is disclosed in a second-price auction (see McMillan, 1994, p. 148). Third, the optimal strategy is easier to understand in a clock auction format than in a second-price sealed-bid auction. We note that the clock auction format has been used successfully for a large number of energy and resource auctions since 2001.

The reverse auction worked in the following way. In each round, each station was given a price offer for one or more relinquishment options. The possible relinquishment options were to go off-air or move to a different band; for instance, a UHF station could bid to move to the High-VHF band or to the Low-VHF band. Price offers for a given station descended from one round to the next. Given the price offers for the round, a bidder could then select its preferred relinquishment option for its station or bid to drop out of the auction. If, after a round, the auction system could not find a feasible assignment for a station in its pre-auction band subject to the various interference constraints, the station was deemed provisionally winning. The winners of the reverse auction were the stations that became provisionally winning in the final stage of the auction.

The reverse auction design described above was able to handle complex interference constraints and multiple relinquishment options without having to solve a complex optimization problem. However, it did not explicitly account for another important departure from the simple model of Section 3.2: the fact that bidders did not necessarily have unit supplies. A number of the bidders owned multiple stations and thus had multi-unit supplies. As such, we would actually expect to observe supply reduction in the reverse auction. Strategic supply reduction is discussed in Section 6.1.

We close this section by discussing another departure from the idealized model of Section 3.2. As described in Section 3.2, we would expect the marginal cost of cleared stations to be increasing and the marginal value of spectrum blocks to be decreasing, so at the first time that revenues exceed clearing costs, the marginal conditions for an optimum are automatically satisfied. However, an exception to this occurs because television channel 37 was reserved for radio astronomy and could not be repacked in the Incentive Auction. As a result, the clearing "overhead" associated with creating an 8^{th} spectrum block is substantial, as channel 37 would be skipped over in the band plan. As we will see below, the marginal cost of clearing an 8^{th} block in the Incentive Auction turned out to be considerably larger than the marginal cost of clearing a 9^{th} block. Under the rules described above, this created the possibility that the stage creating 8 blocks would be the first stage in which the revenues would exceed the clearing costs, but nonetheless, the marginal cost of clearing the 8^{th} block would exceed its marginal value. In this event, the Incentive Auction would inefficiently clear enough television stations to create 8 blocks.

4.2 Forward auction design

We now turn to the forward auction and discuss how the auction design addressed certain real life complications not present in the simple model of Section 3.3.

First, the auction did not offer nationwide licenses. Instead, licenses were offered in 416 geographic areas. This way, smaller bidders that were not interested in nationwide licenses could express their preferences for regional licenses.

Second, forward auction bidders did not necessarily have unit demands. For instance, a bidder could be interested in buying 3 blocks in New York and 2 blocks in San Francisco. To address this complication, the forward auction consisted of an ascending clock auction phase for generic blocks, followed by an assignment phase to map generic blocks to physical frequencies. The use of generic licenses has several advantages (as discussed in Section 2.4), such as reducing the length of the auction and simplifying bidding, compared to the Simultaneous Multiple Round Auction (SMRA) format used in previous FCC auctions.

Another departure from the simple model of Section 3.3 had to do with the competition policy. The FCC wished to have a competition policy that would prevent the two largest wireless operators (Verizon and AT&T) from foreclosing smaller operators in the auction. This is normally accomplished in spectrum auctions via set-asides, which result in discounts for smaller firms as compared to the largest operators. However, the FCC did not wish any discount to interfere with the clearing of the maximum possible amount of spectrum. As a result, the FCC effectively used a conditional set-aside, which would only come into play after the final stage rule is triggered. At this point, the spectrum blocks would "split" into up to three reserved blocks (set aside for smaller firms) and unreserved blocks (available to all bidders).

From that point on, reserve-ineligible bidders could only bid on the unreserved blocks, whereas reserve-eligible bidders could bid on both the reserved and the unreserved blocks.

The two-sided nature of the Incentive Auction required determination of whether the stage would be the final stage of the auction. The *final stage rule* would be met if, after a round, the revenues (i.e. the willingness to pay of forward auction bidders) exceeded the clearing cost. The final stage rule had to be checked after every round of the forward auction because of the competition policy discussed above. This in turn required revenues to monotonically increase during a stage of the auction. Otherwise, there could be a situation where the final stage rule is met after a round but then it is no longer met a few rounds later. This monotonicity requirement ruled out auction formats with package bidding, such as the Combinatorial Clock Auction (CCA).

Speed was an important design consideration. It could take multiple stages to determine the amount of spectrum to be cleared, and it was desirable to reduce the length of each stage. Because most of the revenues in spectrum auctions come from a small number of markets, it was decided to end a stage of the auction if the final stage rule had not been met and there was no excess demand in the top-40 markets, i.e. the 40 (out of a total of 416) geographic areas that typically generate the highest revenues. This allowed the auction to proceed expeditiously to a subsequent stage with a lower clearing target.

4.3 Assignment phase

The use of generic blocks in the ascending clock auction allowed for a quicker and simpler forward auction process, but also presented a design tradeoff. If bidders are unable to express their preferences for particular frequencies until the assignment phase, a part of the forward auction revenue is shifted away from the clock phase to the assignment rounds. On the one hand, efficiency considerations require that these revenues should be accounted for when the final stage rule is being tested. On the other hand, holding assignment rounds after each stage would severely affect the overall speed of the Incentive Auction and put bidders through an awkward exercise of bidding for specific frequencies just to find out that it was all for nothing and the auction would go into the next stage. For this reason, any potential revenues from the assignment phase were excluded when calculating the auction revenue for the purposes of the final stage rule. This decision allowed assignment rounds to be delayed until the final stage of the Incentive Auction, when bidders would be bidding for their actual frequency assignments.

One might think that all of the forward auction revenues can be contained within the clock stage by utilizing some form of a random assignment. For example, the auctioneer can administratively select a specific assignment using some criteria, or let bidders choose their frequencies using a random serial dictatorship approach. If bidders know that there will be no charge for this assignment, then they can allocate all of their monetary resources to the clock phase. But this logic is flawed since such an approach would not allow bidders with nontrivial preferences for particular assignments to express them in the auction, potentially reducing the overall value that they could attain (and revenue they would be willing to pay). Thus, the only way to account for the full revenue is to handle assignments simultaneously with determining allocation—a solution that would not meet the speed requirements of the Incentive Auction.

But there was one design decision that was intended to increase the share of revenues that remained in the clock phase of the auction. The assignment phase was organized as sequential sealed-bid auctions with package bidding that used the Vickrey pricing rule to determine payments. Instead of the Vickrey rule, FCC might have adopted one of the core-selecting rules that are commonly used in spectrum auctions in other countries. However, core-selecting rules are partly motivated by auction literature showing that they can produce higher revenues when compared to the Vickrey rule without a large impact on efficiency. In a regular auction, the auctioneer would pay attention to both objectives and might favor a core-selecting rule. But in the forward auction, the objective was to minimize the revenue collected in the assignment phase in favor of the clock phase, motivating the Vickrey rule.

5. General Performance

The auction required four stages. The clearing target for stage 1 was set at 126 MHz, and turned out to be too ambitious. It was subsequently reduced first to 114 MHz in stage 2, then 108 MHz in stage 3 and finally to 84 MHz in stage 4. The assignment phase was held once, after the forward auction in stage 4.

The biggest surprise in the Incentive Auction was that only one of the four nationwide wireless providers was bidding in the auction until the conclusion of the clock phase. Sprint announced before the auction that it would not participate. Verizon applied to participate in the auction and became a qualified bidder but did not bid in the auction and, as a result, lost its eligibility to bid after the initial round of the auction. AT&T was bidding in the first rounds of the auction, but significantly reduced its requested commitment in the last few rounds of stage 1 and bid to drop out of the auction completely throughout stages 3 and 4.[7] T-Mobile was the only nationwide wireless provider with significant winnings. Other bidders with significant winnings in the auction were Dish and Comcast.

5.1 Efficient clearing

The auction mechanism allowed the quantity of cleared, licensed spectrum to be any number up to ten (paired) blocks. Based on all publicly-available information, the auction achieved exactly the efficient amount of clearing.

Figure 1 shows the clearing cost as a function of the cleared spectrum. The cost of clearing spectrum for the seven-block band plan (84 MHz) was $10.05 billion whereas the cost of clearing spectrum for the eight-block band plan (108 MHz) was revealed to be $40.31 billion (see Table 4 of Appendix A). Thus, the incremental cost of clearing an eighth block would have been $30 billion, which is more than the buyers' combined bids to purchase the first 7 blocks. In the terminology of spectrum valuation, the cost of clearing an eighth block would have been almost $10 per MHz per population ($10 per MHz-pop), which is extremely high.

[7] The auction rules did not allow AT&T to drop out of the auction completely. AT&T's commitment at the conclusion of the clock phase was $894 million. Even though AT&T was not able to drop out of the auction completely, its clock phase commitment was significantly lower than its maximum commitment during stage 1 which was $7.4 billion (after round 21).

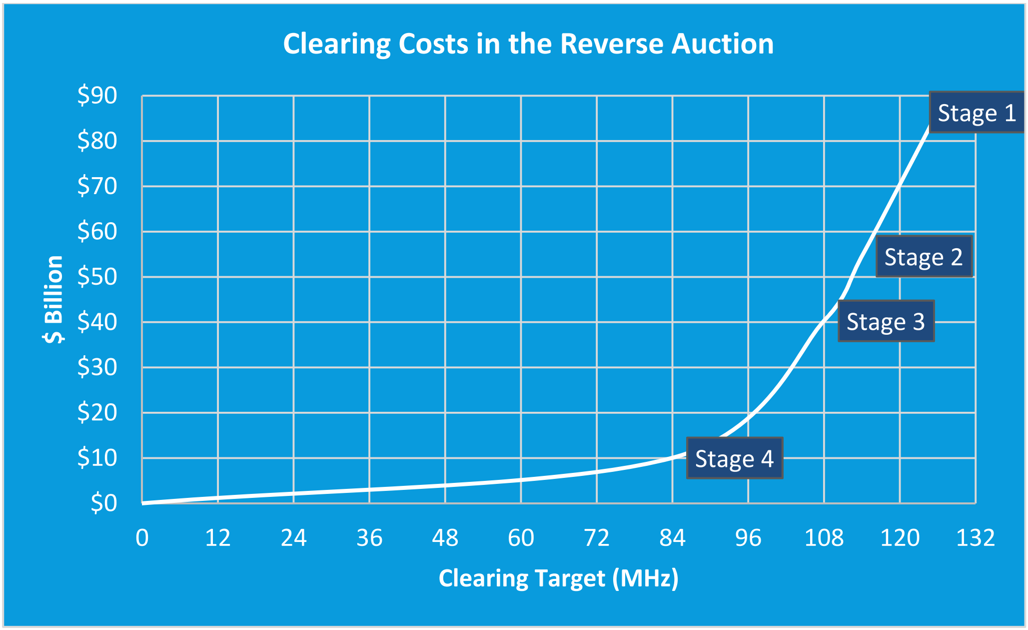

Figure 1: Clearing Costs in the Reverse Auction

Meanwhile, the resulting seven blocks are unimpaired, contiguous to one another, and configured well for international alignment with Canada and Mexico.

5.2 Forward auction proceeds

In 2012, Congress authorized the FCC to conduct the Incentive Auction, to repurpose the 600 MHz band, and Auction 97 for Advanced Wireless Services (AWS-3). $7 billion from the proceeds from those auctions were to be used to fund the First Responded Network Authority (FirstNet) that will provide emergency responders with the first nationwide, high-speed, broadband network dedicated to public safety.

AWS-3, which was conducted in 2015-2016, generated net proceeds (net of bidding credits) of $41.33 billion, which was enough to fully fund FirstNet. As a result, when the Incentive Auction started it was known that it would not need to raise any funding for FirstNet. The Incentive Auction, which was conducted in 2016-2017, generated net proceeds of $19.31 billion. AWS-3 and the Incentive Auction achieved the highest revenue and the second highest revenue, respectively, across all FCC auctions. Thus, the package of AWS-3 and the Incentive Auction was extremely successful, as it provided a large amount of spectrum for wireless use, repurposed the 600 MHz band, funded FirstNet, and generated a significant amount to be applied to deficit reduction.

Still, the revenues of the Incentive Auction have been compared (unfavorably) to the revenues of the AWS-3 auction. The significant difference in revenue between the two auctions is largely due to the different levels of participation by AT&T and Verizon in the two auctions. AT&T and Verizon were the two biggest winners in AWS-3. However, in the Incentive Auction, Verizon did not bid and AT&T was bidding to drop out of the auction completely after the first part of the auction. If AT&T and Verizon had behaved in a similar way in the AWS-3 auction, our estimate is that the AWS-3 auction would have generated net proceeds of less than $16.5 billion.

In the initial round of the auction, AT&T had the largest eligibility and largest commitment across all bidders. Its requested commitment peaked at $7.5 billion and its (processed) commitment peaked at $7.4 billion, both after round 21 of stage 1. But then, between rounds 22 and 26 of stage 1, AT&T reduced its requested commitment to only $61.6 million, bidding only for Category 2 products (a safe parking strategy, as discussed in Appendix B). In round 2 of stage 1, AT&T further reduced its requested commitment to $10.8 million, again bidding only for Category 2 blocks. In all later rounds and until the conclusion of the clock phase, AT&T was consistently bidding to completely drop out of the auction, submitting zero quantity bids for all products.

A plausible explanation for the reversal in AT&T's bidding strategy is that the company's priorities changed at the time that the deal with Time Warner was made. Even though the deal was announced in October 2016, it has been reported that the first meeting between the CEOs of the two companies occurred on August 25,[8] that is, a few days before rounds 22-27 of stage 1 which occurred August 29-30. An alternative plausible explanation is that AT&T expected to win the FirstNet contract (which it was eventually awarded a few months later) to build a nationwide 700 MHz network for public safety, removing AT&T's need for additional low-band spectrum.

The auction rules were fairly robust to the reversal in AT&T's strategy, because a bid to reduce demand for a product could only be applied to the extent that it would not cause excess supply (no excess supply rule, see Section 7). Thus, AT&T ended stage 1 with a commitment of $4.2 billion, even though its requested commitment at the end of stage 1 was only $61.6 million. Because the final stage rule was not met in stage 1, AT&T was able to reduce its commitment at the beginning of every new stage, as the supply of most products was reduced by one. Still, because every new stage was designed to be a continuation of the previous stage, AT&T's commitment could not be reduced to its requested commitment of $0. AT&T's commitment at the conclusion of the clock phase was $894.1 million.

Comparison with Auction 97 (AWS-3)

The AWS-3 Auction was a simultaneous multiple round auction which generated record net proceeds of $41.33 billion. In order to obtain an estimate of the AWS-3 net proceeds in a scenario where the behavior of AT&T and Verizon is along the lines of what it was in the Incentive Auction, we conducted a simulation.

Using the publicly available bid information for AWS-3, we estimated a bidder's valuation for a license to be equal to the maximum bid amount that the bidder submitted for that license. With the exception of Dish, we estimated a bidder's budget to be equal to its maximum commitment across all rounds. For Dish, we assumed that its net budget was equal to $10 billion. This is consistent with Dish's bidding, across its three affiliates, and the fact that Dish returned some of the licenses it won after the auction when the FCC determined that Dish should not have qualified for a bidding credit.[9]

[8] Code Names and Covert Meetings in AT&T's Courtship of Time Warner, The New York Times. Oct 24, 2016.

[9] We note that this approach could be underestimating a bidder's valuation for a license in the event that the bidder won that license in AWS-3. An upper bound on revenues in the scenario where the level of participation for AT&T and Verizon is similar to the Incentive Auction can be calculated by summing the payments of AT&T and Verizon for the Incentive Auction with each other bidder's estimated budget for AWS-3. This approach yields an upper bound of $17.9 billion for the net proceeds that AWS-3 would have generated if the level of participation of AT&T and Verizon had been similar to the Incentive Auction. We note that $17.94 is still lower than the net revenue of the Incentive Auction.

We simulated the simultaneous multiple round auction assuming that in each round every bidder (except for Verizon and AT&T) bid on the most profitable set of licenses subject to its budget constraint, given the provisionally winning bids from the previous round. We assumed that Verizon did not participate in the auction. Finally, we assumed that AT&T stopped bidding in the auction during round 46 because this allowed for AT&T's final commitment to be very close to its final commitment in the Incentive Auction.

Table 1 shows, for each of the main bidders, the bidder's actual net payment in AWS-3 as well as its simulated net payment under the assumptions listed above. We find that if AT&T and Verizon had bid similarly to the Incentive Auction, the AWS-3 net payment would be reduced to $16.5 billion.

Table 1

Winning Bidder	Actual AWS-3 Net Payment	Simulated AWS-3 Net Payment
AT&T	$18,189,285,000	$ 896,501,000
Verizon	$10,430,017,000	$ 0
Dish / SNR Wireless / Northstar	$ 9,995,567,775	$ 9,989,998,000
U.S. Cellular / Advantage Spectrum	$ 338,304,000	$ 338,289,000
T-Mobile	$ 1,774,023,000	$ 3,499,989,000
2014 AWS Spectrum Bidco	$ 291,810,000	$ 817,271,000
Puerto Rico Telephone Company, Inc.	$ 170,901,300	$ 125,188,000
All other bidders	$ 139,765,250	$ 797,664,000
Total	**$41,329,673,325**	**$16,464,900,000**

5.3 Clearing target selection and auction duration

Bidding in the Incentive Auction commenced in March 2016 and concluded in March 2017. A total of 372 bidding rounds were conducted. Table 2 shows the number of rounds for each part of the auction.

Table 2

	Number of Reverse Auction Rounds	Number of Forward Auction Rounds
Initial Commitment	1	-
Stage 1	52	27
Stage 2	53	1
Stage 3	52	1
Stage 4	53	58
Assignment Phase	-	74
Total	211	161

One potential criticism of the Incentive Auction is that it lasted too long. If, after the initial commitment, the FCC had selected a clearing target of 84 MHz (instead of 126 MHz), it is very likely that the auction would have concluded after a single stage with significantly fewer rounds. As described below, an initial clearing target of 84 MHz would have had the additional advantage of reducing strategic bidding in the forward auction.

Once reverse auction bidders submitted their initial bids in the initial commitment period, the FCC used these bids as input to a clearing target optimization procedure which determined 126 MHz as the clearing target for stage 1. The clearing target was announced to bidders and the reverse auction for stage 1 was conducted. This determined that the cost for clearing 126 MHz was $84.6 billion. The clearing cost was made public before bidding for the forward auction of stage 1 commenced. This cost significantly exceeded all estimates on forward auction proceeds. As a result, forward auction bidders bid in stage 1 expecting that stage 1 would not be the final stage, which might have motivated forward auction bidders to use certain strategies to park eligibility during stage 1 (see Section 7.5 and Appendix B).

The FCC had adopted procedures to conduct forward auction bidding in stage 1 regardless of the clearing cost in order to attempt to clear the maximum amount of spectrum. Similar considerations motivated the FCC's decision to select the next lowest clearing target in the 600 MHz band for any subsequent stage.

We now describe an alternative clearing target determination which would have likely resulted in selecting a lower clearing target for stage 1. The FCC would run the clearing target optimization procedure to determine a *provisional* initial clearing target. Reverse auction bidding for stage 1 would start with that clearing target (e.g. 126 MHz). However, if after any reverse auction round the cost for all provisionally winning reverse auction bidders exceeded some threshold, then the clearing target would be reduced and reverse auction bidders would continue bidding for the lower clearing target (without conducting a forward auction in between). The threshold would represent an upper bound on the expected forward auction revenues and could depend on the clearing target (e.g. the threshold could be $60 billion for 126 MHz and $50 for 114 MHz). This approach would have reduced the duration of the auction but also possibly reduced the prevalence of parking in stage 1 of the forward auction, because forward auction bidders would only be asked to bid for a clearing cost that could potentially be covered with forward auction proceeds.

An alternative approach for reducing the duration of the auction would be to only use the most spectrally efficient clearing targets. For instance, the FCC could have skipped the 108 MHz clearing target which has 8 forward auction licenses of 10 MHz each but requires clearing 108 MHz, an inefficiency that is a consequence of channel 37. This approach would have reduced the duration of the auction (by about 53 rounds) but would not have reduced the incentive for parking in the forward auction of stage 1.

6. The Reverse Auction

The reverse auction appears to have performed well in terms of inducing bidders to participate in the auction. The FCC has not published the names or the number of stations that made initial commitments to participate in the auction, but the fact that the initial clearing target was 126 MHz suggests that the number of participating stations was large.

The reverse auction also performed well in terms of clearing 84 MHz at a reasonable cost. However, the cost for clearing more than 84 MHz appears to be very large. Specifically, the incremental cost in going from 84 MHz to 108 MHz (8th block) was $30 billion, the incremental cost in going from 108 MHz to 114 MHz (9th block) was $14 billion, and the incremental cost in going from 114 MHz to 126 MHz (10th block) was $32 billion (see Table 4 in Appendix A).

The cost of clearing more than 7 blocks is partly explained by increasing marginal costs and the fact that the larger clearing targets had to accommodate channel 37. As shown in Figure 2 below, clearing targets above 84 MHz had to clear additional spectrum compared to the 84 MHz clearing targets because of the required guard bands around channel 37 and between the TV band and the wireless band.

Figure 2: 600 MHz Band Plans

Strategic bidding by reverse auction bidders could have also contributed to increasing the clearing costs. The effect of strategic bidding in the clearing cost may have been greater when the FCC attempted to clear a larger quantity of spectrum, as it did in the first three stages of the auction.

One of the main objectives of the reverse auction design was to make it obvious to a small broadcaster that it was a dominant strategy to bid its cost. This notion was captured by obvious strategy-proofness (Li, 2017; Milgrom and Segal, 2017). Since it is not possible to achieve obvious strategy-proofness for all types of bidders, the goal was reduced to achieving obvious strategy-proofness for single-minded bidders (bidders that have unit supplies). In particular, the design is obviously strategy-proof for bidders that owned a single station and that only selected one relinquishment option (e.g. to go off-air) when applying to participate in the auction. However, the design is not strategy-proof for a bidder that owns multiple stations nor for a bidder that owns a single station but has selected multiple relinquishment options on its application.

We next provide evidence suggesting that some bidders with multiple stations might have strategically reduced supply in the auction. We then discuss why a bidder that can bid on multiple relinquishment options might find it beneficial to deviate from truthful bidding. We conclude that the reverse auction design, which focused on obtaining an obviously strategy-proof mechanism for single-minded bidders, could have paid greater attention to limiting the gaming by multi-minded bidders.

6.1 Strategic supply reduction

A bidder that owns multiple stations in a certain market might find it beneficial to strategically reduce its supply in the auction. For example, consider a bidder that owns two stations that interfere with each other. By dropping out of the auction for one station early on (or by only signing up one station for the auction), the bidder may be able to cause its other station to become provisionally winning at a high price. Strategic supply reduction can significantly increase the clearing cost (Doraszelski, et al., 2016).

We note that strategic supply reduction is not risk-free as the bidder does not know which other stations are bidding in the auction and thus cannot be sure that dropping one of its stations out of the auction will cause its other station(s) to become provisionally winning. Still, it is a strategy that bidders could employ, along the lines of a demand reduction strategy in a forward auction (Ausubel, et al., 2014). Some evidence of potential supply reduction in the reverse auction is provided by the auction results for spectrum speculators that acquired TV licenses in anticipation of the Incentive Auction.

OTA Broadcasting is a private equity firm founded by Michael Dell's MSD Capital that acquired a number of TV licenses before the auction. According to its website (http://otabroadcasting.com/), OTA Broadcasting owned 24 stations before the auction. Ten of these stations were sold in the Incentive Auction. It is plausible that OTA Broadcasting employed supply reduction strategies in any of four local markets. In the Pittsburgh market, OTA Broadcasting owned 11 stations before the auction but sold only five of those stations. In the San Francisco market, OTA Broadcasting owned two stations before the auction and sold one of those stations. In the Charlotte market, OTA Broadcasting owned two stations before the auction and sold one of those stations in the Incentive Auction.

Finally, OTA Broadcasting owns a station in Wilkes Barre-Scranton, PA and also owned a station in New York before the auction. Though these two stations do not interfere with each other, the Wilkes Barre-Scranton station interferes with several stations in New York. OTA Broadcasting did not sell its Wilkes-Barre station but did not sell its New York station in the auction. It is plausible that by not selling the Wilkes-Barre station, OTA attempted to cause the UHF band to be more congested in New York, which in turn caused its New York station to become provisionally winning when other New York stations dropped out of the auction, earlier than it would have otherwise.

NRJ TV LLC, another private equity firm that acquired TV licenses before the Incentive Auction, potentially conducted supply reduction in the Los Angeles and San Francisco markets. In each of those markets, NRJ TV owned two or more stations but only sold one station in the auction.

6.2 Strategic bidding with multiple relinquishment options

A second-order effect with respect to strategic behavior is the absence of strategy-proofness for a single-station owner that selected multiple relinquishment options on its application. A bidder could select up to three relinquishment options for each of its stations when it applied to participate in the reverse auction: Go off-air, Move to Low-VHF, and Move to High-VHF. The algorithm that calculated the price offers for each relinquishment option of a station used vacancy information. A station's vacancy in each band depended, among other things, on the station's currently held option. Thus, a bidder interested in moving to High-VHF (from UHF) could potentially achieve higher a price offer for moving to High-VHF by bidding to go off-air in the early rounds of the auction and then bidding to move to High-VHF a few rounds before it expected its station to become provisionally winning. Of course such a strategy is risky because if, in this example, the station became provisionally winning while it was bidding to go off-air in the final stage of the auction, it would have committed to go off-air and thus would be required to stop broadcasting after the auction.

7. The Clock Phase of the Forward Auction

In the clock phase of the forward auction, generic licenses were sold in 416 geographic areas (referred to as Partial Economic Areas, or PEAs). A product was the pairing of a PEA and a license category.

Before the final stage rule was met, there could be at most two categories within each PEA: Category 1 (with impairment up to 15%) and Category 2 (with impairment between 15% and 50%). After the final stage rule was met, Category 1 could be further split into two categories: reserved and unreserved. Only a few PEAs actually had Category 2 blocks in stage 1, and they all had disappeared by stage 4.

The clock phase was organized as a clock auction with intra-round bidding. In each clock round, the auctioneer quoted a range of prices for each product.[10] Each bidder had a choice between maintaining its demand over the entire price range or requesting to change its demand at any price within the range. The clock prices of products with excess demand were incremented for the next round.

A bid to change demand was considered a request, which the auctioneer attempted to fulfill during bid processing subject to two constraints:

- **No excess supply**: A bid was not applied if it would create or increase excess supply. In particular, if aggregate demand for the product was greater than or equal to supply, the product's aggregate demand after applying the bid could not drop below supply.
- **Activity rule:** The total number of bidding units associated with the bidder's demand after applying the bid could not exceed the bidder's eligibility in the round.

The "no excess supply" rule was applicable to bids for reducing demand. It guaranteed that (unless the product's supply increased in a later stage) all licenses that were in demand in prior rounds would be assigned, and the auction proceeds are non-decreasing within a stage. The activity rule is standard practice in spectrum auctions. It comes into play when a bidder simultaneously bids to increase demand for one product and reduce for another product but the latter bid could not be applied because of the "no excess supply" rule.

All bids were processed in increasing order of price points, breaking ties with pseudorandom numbers.[11] For instance, if a product had one unit of excess demand and two bidders submitted bids to reduce demand by one block each (and no other bidder bid to change its demand for that product), only the bid at the lowest price point would be processed.

Due to the main design objectives, bidders in the forward auction were not able to use the full flexibility of package bidding. One of the innovations for the forward auction was providing bidders with additional ways to express their preferences. In particular, bidders were allowed to use different types of bids to express how they wanted the auction system to handle their demand changes in case it caused a violation of one of the bidding constraints mentioned above. Bidding options included simple bids, switch bids, all-or-nothing bids, and all-or-nothing bids with backstopping. Details about the bid types and their usage statistics are provided in Appendix B.

7.1 Reserved spectrum

Concentration in telecommunications markets is a large concern in the US and worldwide. In 2015, the time of key design decisions for the Incentive Auction, the market shares in wireless subscriptions were 34% and 33% for AT&T and Verizon, and only 16% each for Sprint and T-Mobile. Furthermore, the two

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[10] With the exception of the opening round (round 1 of stage 1) where bidders simply declared their demands at the opening prices.

[11] A bid's price point is defined to be the percentage of the distance between the bid price and the lowest price in the round over the price range for the product.

largest nationwide operators held 73% of sub-1-GHz spectrum, whereas the two smaller nationwide operators accounted for only 15% of the valuable low-band spectrum.[12] Given the market situation, the FCC adopted a protection mechanism to reserve spectrum for smaller bidders which took the form of a "conditional set-aside" that would create the reserved product but only after the set-aside eligible bidders paid their fair share towards the clearing costs.

It is worth mentioning that the reserved product was not identical to the corresponding unreserved product due to resale restrictions (the reserved product cannot be sold to reserve-ineligible bidders in the post-auction market). For this reason, the unreserved price was expected to be at least as high as the reserved price.

Since Verizon did not participate and AT&T lost its interest in stage 1, essentially all the active bidders at the time that the set-aside was triggered (in stage 4) were reserve-eligible in all PEAs.[13] Thus, the spectrum reservation policy employed by the FCC was nonbinding. However, this fact does not prove that the policy was unnecessary because bidders might have taken different actions if there were no reserved spectrum. It is equally likely that the policy was successful in making a foreclosure strategy impossible and in encouraging or emboldening participation by smaller bidders. We conclude that some form of spectrum cap and/or reservation continues to be very relevant for future auctions.

At the same time, some of the implementation details appear to have had some degree of negative effects. First, bidding became more complex because the number of relevant products for each bidder was doubled, which potentially increased the likelihood of mistakes by bidders. Second, in some instances the reserved price was higher than the unreserved at the conclusion of the clock phase, even though the unreserved product is at least as valuable as the reserved.[14] More importantly, this implementation may have increased the duration of the auction, because in some cases two rounds were required in order to increase both prices by one increment even though only one round would have been required for a single product.

An obvious improvement to the reservation policy would be to create a reserved product in a given PEA only if at least one of the bidders were not reserve-eligible in this PEA. Then the reserved products would not have been created for those 69 PEAs in which all bidders were reserve-eligible.

A more general improvement would have been to trigger the spectrum reserve only if there were enough bidders bidding in the auction that could not qualify to be reserve-eligible in all PEAs. If this rule had been in place, the spectrum reserve would not have been triggered in the Incentive Auction because Verizon was not bidding. Note that under this approach, bidders would have learned whether both AT&T and Verizon were bidding in the auction at the trigger time. This informational consequence

[12] See FCC, *Mobile Spectrum Holdings Report and Order*, 2014, ¶62.

[13] The only bidders that could not qualify to be reserve-eligible in all PEAs were AT&T and Verizon. However, even AT&T and Verizon were reserve-eligible in some PEAs. Furthermore, 69 PEAs had the property that all bidders could be reserve-eligible there.

[14] In 140 PEAs, the unreserved price was larger than the reserved (in most cases 4-25% larger). In 195 PEAs, the unreserved price was equal to the reserved. In 81 PEAs, the unreserved price was smaller than the reserved; in most of those cases the reserved price was within one price increment of the unreserved, but there were a few cases where the two prices were two or more increments apart.

would only occur towards the end of the auction and does not appear to have significant negative effects.

Finally, the auction design could have avoided the possibility of the reserved price being higher than the unreserved by adopting a different rule for incrementing prices. The price of a reserved (resp. unreserved) product in the auction was incremented if there was excess demand for that product, regardless of there was excess demand for the unreserved (resp. reserved) product in that PEA. An alternative would be to increment prices in a way that guarantees that the price of the unreserved is always greater than or equal to the price of the reserved.

7.2 Final stage rule

The final stage rule included two components. The first component required that the cumulative forward auction proceeds exceed an exogenously set threshold that reflects competitive prices. The second component required that forward auction proceeds (net of bidding credits and impairment discounts) be sufficient to cover the clearing cost for the stage, the estimated relocation costs for TV stations, and the cost of running the auction. Both components had to be satisfied in order for the final stage rule to be met. The final stage rule thus imposed two aggregate reserve price conditions: one based on what the FCC considered to be competitive prices, and the other based on the clearing cost of the reverse auction.

An aggregate reserve price condition requires that the sum of bids across all bidders is sufficiently high. The usage of aggregate reserve prices causes a free-rider problem. In particular, a bidder may refrain from increasing its bids because it expects or hopes that other bidders will bid sufficiently high to meet the aggregate reserve price. This could reduce the chances that the aggregate reserve is met (and increase the chances that the auction fails).

The second component of the final stage rule (the cost component) was mandated by the Spectrum Act and represented a reasonable aggregate reserve price as it reflected the value of the spectrum to TV stations. The first component was a policy decision.

In general, guaranteeing competitive prices via an aggregate reserve price can lead to overshooting. It is tempting for the regulator to set opening prices for all products at very conservative levels and then use the aggregate reserve price to ensure competitive revenues. However, the regulator can easily set aggregate reserve price too high. This risk is particularly relevant when ‘competitive levels‘ are derived based on previous auctions (since market conditions might have changed).

For the Incentive Auction, it appears that the threshold for the first component of the final stage rule had been set dangerously high. In stage 4, the first component required that the average price per MHz-pop be at least $1.25.[15] The average price per MHz-pop at the end of the clock phase was only $1.27, just two cents above the threshold. To put it differently, the auction experienced a “near miss”. In stage 4, the cost of the reverse auction dropped from $40.3 billion to $10.05 billion and, as a result, the second component of the final stage rule was met before the clock phase started. However, the first component of the final stage rule was not met after round 1. In round 2, T-Mobile increased its demand in Los Angeles from 2 to 3 blocks triggering the final stage rule. If T-Mobile had not increased its

[15] More precisely, the first component required that the average price per MHz-pop for Category 1 products in the top-40 PEAs is at least $1.25.

demand in Los Angeles, it is quite plausible that the final stage rule would not have been met in stage 4 (see also discussion in Section 7.3) which would have caused the auction to proceed to stage 5 with a lower and inefficient clearing target.

The FCC has utilized aggregate spectrum reserve prices in previous auctions. In some cases, the aggregate reserve price was along the lines of the second component of the final stage rule in the sense that it was required to cover relocation costs.[16] In another case, the aggregate reserve price was along the lines of the first component.[17]

If a reserve price that aggregated to a higher amount than the sum of the individual opening prices in the top-40 PEAs was desired in the forward auction, it would have been better to accomplish this objective by raising the individual opening prices commensurately, instead of establishing an aggregate reserve. This would have avoided the creation of an unnecessary free-rider problem and mitigated the risk associated with the aggregate reserve.

7.3 Extended round

The extended round was another innovation in the context of the Incentive Auction. It was designed to give bidders in the forward auction a last chance to meet the final stage rule in the current stage and thus avoid having the clearing target reduced. Intuitively, if triggered, the extended round would prolong the stage to see whether sufficient revenues could be recovered by increasing prices for products in the top-40 PEAs without excess supply.[18]

No extended round was triggered in the auction. In stages 1-3, the forward auction proceeds were substantially less than the clearing cost generated by the reverse auction. According to the rules, the auction then skipped the extended round and proceeded directly to the next stage, with a lower clearing target. In stage 4, the cost of the reverse auction dropped from $40.3 billion to $10.05 billion and, as a result, the cost component of the final stage rule was met immediately eliminating any need for the extended round.

In the hypothetical scenario where T-Mobile would not have increased its demand in Los Angeles in round 2 of stage 4, it is plausible that an extended round would have been triggered. Whether the final stage rule would have been met due to the extended round depends on whether the bidders, collectively, would have wanted the extended round to succeed. Since AT&T was trying to get out of a

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[16] In Auction 66 (AWS-1) in 2006, the FCC established an aggregate reserve price for all AWS-1 licenses in order to implement a Congressional mandate to recover estimated relocation costs of government incumbent operators in the band. In Auction 97 (AWS-3), the FCC used an aggregate reserve price for each sub-band based on the total estimated relocation or sharing costs contained in the Federal agencies' transition plans.

[17] In Auction 73 in 2008, the FCC used aggregate reserve prices for each block (across multiple geographic areas) to promote the recovery of a portion of the value of the public spectrum resource. The aggregate reserve price for each block was set based on a variety of factors, such as the characteristics of the band and auction prices of other recently auctioned licenses (Cramton, et al., 2007).

[18] An extended round would be triggered if, after the bid processing of a round, (i) the final stage rule was not met, (ii) there was no excess demand in the top-40 PEAs, and (iii) the final stage rule would be met under a scenario where the prices of the top-40 PEAs increased by 20% and all bidders maintained their demand. The extended round increment would then be set at 133% of the increment required to meet the final stage rule, which would make it possible for the final stage rule to be met even if some bidders did not maintain their demand at the extended round clock prices.

number of top-40 markets in stage 4, it is likely that the extended round would have failed and the auction would have proceeded to stage 5.

More generally, when the extended round was designed it had not been anticipated that a bidder holding demand in multiple top-40 markets would be trying to reduce its demand at a price that it previously accepted. In such scenarios, the likelihood that an extended round can help to achieve clearing is minimal.

7.4 Unassigned licenses

In the final stage of the auction, supply included 7 blocks in each of the 416 PEAs, corresponding to a total of 2,912 licenses. 2,776 of these licenses were sold in the auction and only 136 remained unassigned.

Most notably, there was one unassigned license in Los Angeles (PEA002) and two in San Diego (PEA018). This occurred despite the fact that for each of these PEAs, the aggregate demand at the final clock price of stage 1 exceeded 7 blocks.

The unassigned licenses in Los Angeles and San Diego were caused both by insufficient demand for those PEAs in stage 4 and by the fact that the supply in each of these PEAs had increased from stage 1 to stage 4. The latter was a consequence of an agreement between the FCC and the Mexican communications regulator, the *Instituto Federal de Telecomunicaciones* (IFT), whereby the two agencies agreed to a channel plan which identified future channels for operating Mexican stations along the border with the United States that essentially moved all Mexican channels below channel 37 (with a few exceptions that are listed in the coordination documents). However, the auction design was finalized before the agreement between the FCC and IFT was made and did not contemplate the possibility that supply could increase between stages.

7.5 Strategic bidding

The main attempts for bidding manipulation that we observed in the clock phase of the forward auction had to do with "parking" eligibility with the goal of delaying bids that reflected bidders' true preferences. Bidders tended to park their eligibility in top PEAs (licenses with the most bidding units) and in Category 2 products. Parking eligibility in Category 2 products was a reasonably safe strategy because bidders could reduce their demand for those products at the beginning of a new stage (an exception to the "no excess supply" rule). However, Category 2 products were scarce and offered comparatively few parking spaces. As a result, bidders also attempted to use Category 1 products in top PEAs to park the rest of their eligibility. As we shall see, parking in top PEAs proved to be a riskier strategy for bidders.

The prevalence of parking in the first stage of the auction might have been due to the fact that bidders did not expect stage 1 to be the final stage. At the time that bidding in the forward auction started, bidders knew that the clearing cost was $86.4 billion and thus the forward auction net proceeds would need to be at least $88.6 billion for the final stage rule to be met. This number significantly exceeded expectations on net forward auction proceeds, thus bidders were pretty confident that the final stage rule would not be met in stage 1. Nevertheless, because a new stage was designed to be a continuation of the previous stage, bids made in stage 1 for Category 1 products could not necessarily be reversed in later stages.

A detailed analysis of "parking" including examples and risk assessment can be found in Appendix B.

8. The Assignment Phase

The clock phase of the forward auction determined the number of generic blocks for each product awarded to each bidder. The purpose of the assignment phase was to map generic winnings into actual physical frequencies. The physical frequencies associated with seven blocks were labeled from A to G, with G being the block with the highest frequency in the band. Auction rules specified that all potential assignments in each region have to be as contiguous as possible. Given that the Incentive Auction has cleared seven blocks (all above channel 37), it was possible to guarantee a contiguous assignment for all winners of multiple blocks in each region. The assignment phase was organized as a sequential sealed-bid auction where bidders bid for specific frequency assignments in each region (PEA) independently, one after another, in a descending order of population. Participating bidders were informed about their own assignments in each region before bidding for their assignments in the next region.

Bidding in the assignment phase was optional since winners of the generic blocks were guaranteed some assignment. For example, a bidder who was indifferent between all of its possible assignment options did not need to bid at all. In fact, 18 out of 50 clock phase winners chose not to bid in the assignment phase. Furthermore, only about 0.7% of forward auction proceeds came from the assignment phase, suggestive that all seven blocks were viewed by bidders as nearly equivalent and that it was appropriate to treat all blocks as generic spectrum in the clock phase.

In Figure 3 we summarize the results of the assignment phase. The figure depicts the percentage of the US population covered by the largest winners for each frequency block.

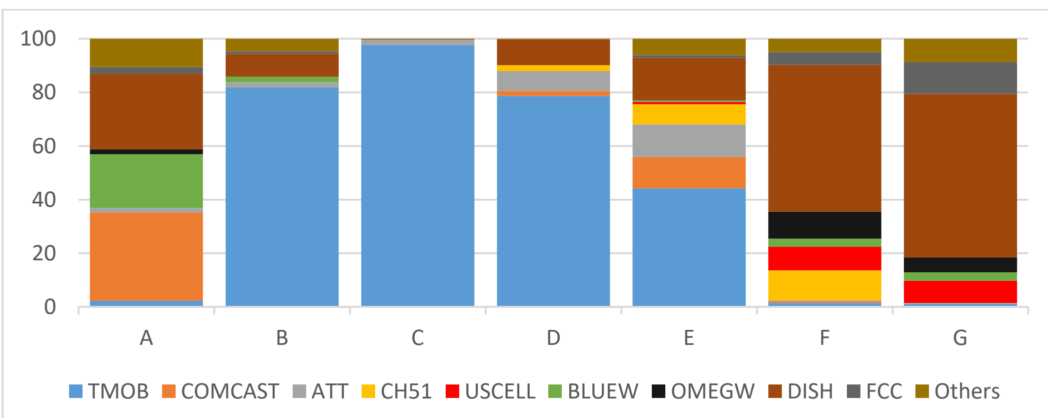

Figure 3: Percentage of Population Covered by Large Winners

Given the total of 416 PEAs, processing regions one by one would have taken a long time. To facilitate a faster process and to produce a less fragmented assignment, the FCC introduced two features: grouping and parallel bidding.

8.1 Grouping of PEAs and parallel bidding

The grouping feature allowed the FCC to merge several regions into a larger aggregation for a simultaneous assignment. In particular, regions were grouped when the same assignment could be made in all of the regions in the group for each clock phase winner.[19]

The rationale behind grouping regions is as follows. When designing a spectrum auction, the regulator faces an important "product design" decision about how finely to partition the country into licenses. If the partition is too coarse, small bidders could be seriously harmed because they are forced to bid on large regions that do not match their footprint. In contrast, if the partition is too fine, the number of products, the complexity and the duration of the auction are unnecessarily increased. In general, there is a preference of erring on the finer side, because a finer partition, albeit the auction complexity, does not preclude bidding and allows bidders to assemble larger aggregations. In this context, grouping of regions in the assignment phase can be viewed as a systematic way of undoing any "too fine" partition errors by ensuring that each bidder is assigned the same frequencies in each of the regions in a group, increasing the efficiency of the assignment.

The parallel bidding feature was introduced to further shorten the duration of the assignment phase. After all major markets (top-40 PEAs) have been assigned, the FCC started to run parallel independent assignment auctions in regions that are far away from each other geographically (regions from different REAGs[20], one region from each predefined REAG). The parallel bidding reduced the amount of feedback that bidders would have received in a fully sequential process, but, at the same time, the value of such feedback (specific frequencies a bidder won in a region far away) appear to be insignificant in most cases.

The grouping of PEAs and the parallel bidding for REAGs seemed to work well. Many the groupings consisted of PEAs that were close geographically and thus facilitated the goal of assigning a bidder the same set of licenses in a region. Some of the groupings consisted of a large number of PEAs, especially during parallel bidding. For instance, in round 27, in REAG 3, the grouping consisted of 22 PEAs out of which 21 were in Wisconsin and Iowa. As another example, in round 27, in REAG 5, the grouping consisted of 16 PEAs out of which 14 were in Texas. There were, however, some exceptions, particularly in the top-40 PEAs. The most notable exception is probably the grouping of assignment round 5 which consisted of Orlando (PEA013), Portland (PEA019), Pittsburgh (PEA023), and Fresno (PEA034).

If PEAs had not been grouped and no parallel bidding had been conducted, an assignment round would have been required for each PEA and thus the number of required assignment rounds would have been 416. In comparison, the actual assignment phase consisted of only 74 assignment rounds.

8.2 Vickrey payment rule

For the assignment phase, the FCC adopted a VCG payment rule in order to encourage bidders to bid according to their true values. While the VCG rule has good incentive properties, it also known to have some undesirable features (see Ausubel and Milgrom (2006)). The culprit of the problems traditionally associated with the VCG rule is that the payments are not guaranteed to be in the core (i.e., bidders may

[19] A necessary condition for grouping was for each region in a group to have the same clock phase winners and winnings.
[20] REAG stands for Regional Economic Area Grouping. FCC predefined 6 REAGs.

pay less than the amount offered by their competitors). This shortcoming has motivated the use of core-selecting payment rules[21] in recent spectrum auctions in the UK, Canada and Australia.

The bidding data from the assignment phase of the Incentive Auction presents us with a unique opportunity to evaluate the extent of the core problem of the VCG. Treating bids as true values, we find that 38 instances (out of 228 total assignment auctions held by FCC) where VCG payments are too low to be in the core. The cumulative revenue shortage across all assignment auctions is $4,411,699. That is, assuming the same set of bids, if the FCC had used a core-selecting payment rule, the assignment phase gross revenues would have been $140,342,331 instead of $135,930,632, that is, about 3.25% higher. However, given that core-selecting auctions are not incentive-compatible in general (i.e., bidders can gain by bidding in a non-truthful manner), the implications of this comparison are quite limited.

Ausubel and Milgrom (2006) provided a well-known example of the VCG rule where winners pay zero even though losers bid competitively. Their theoretical example was driven by the same core problem of the VCG rule described above. Using the bidding data from the assignment phase, we find 3 instances (out of the 38 instances with core violations) where bidders literally pay zero. To the best of our knowledge, it is the first time that the "zero revenue" irregularity of the VCG rule has been observed in practice. We provide details for one of these instances below.

Example of "Zero Revenue" Outcome – PEAs 224 and 287 (Assignment Round 37, REAG 3)

The assignment for seven blocks in PEAs 224 and 287 (De Kalb, IL and Kenosha, WI) was made in round 37 (one of the rounds with parallel bidding). In this region, Dish Networks won one generic block, while T-Mobile and U.S. Cellular won three generic blocks each. The assignment phase bids submitted by bidders for this region are listed in Table 3.[22]

Table 3: Assignment Bids for PEAs 224 (excluding infeasible bids)

Bidders	*Dish Network*	*T-Mobile*	*U.S. Cellular*
Bids:	**Bid $0 m for A**	Bid $0.4 m for ABC	Bid $0 m for ABC
	Bid $0 m for D	**Bid $3.5 m for BCD**	Bid $0 m for BCD
	Bid $0.237 m for G	Bid $0.01 m for DEF	Bid $4.0 m for DEF
		Bid $0 m for EFG	**Bid $8.7 m for EFG**
VCG payment:	0	0	0

The mechanics of the VCG payment calculations for this example are as follows. First, observe that U.S. Cellular's bid of $8.7 m for blocks EFG prevented Dish Network from winning block G. Second, T-Mobile's bid of $3.5 m for blocks BCD prevented Dish Network from winning block G because winning it would have forced U.S. Cellular to a noncontiguous assignment. Therefore, in the absence of either T-Mobile or U.S. Cellular, Dish Network would still have been assigned block A. As a result, the VCG payment of U.S Cellular equaled zero! Clearly, T-Mobile and U.S. Cellular paid to the FCC less than the amount offered by Dish Network for block G. In contrast, a core-selecting rule in this situation would

[21] See Day and Raghavan (2007), Day and Milgrom (2008), and Day and Cramton (2012).
[22] Infeasible bids (ones that could not win) are omitted here. See Section 8.3 for additional details about infeasible bids.

have increased the joint payment of T-Mobile and U.S. Cellular to $0.237 m and avoided the “zero revenue” outcome.

“Zero revenue” outcomes and the high incidence of outcomes that lie outside of the core raises an important question about the FCC’s motivation for adopting the VCG rule instead of a core-selecting rule. One potential explanation is as follows. The VCG rule sometimes allows bidders to acquire desired frequencies cheaply. Expecting a relatively cheap assignment round, bidders can afford to bid higher for the generic blocks in the allocation phase. For the Incentive Auction, only revenues from the allocation phase counted towards meeting the final stage rule. So there was a desire to pack as much revenues into the allocation phase as possible, resulting in a decision to make the prices in the assignment phase as low as possible.

8.3 Concealing feasible assignment options

With the adoption of the VCG rule, there was a need for mitigating measures to make it harder for bidders to manipulate the assignment phase and damage their opponents. Another innovation made by the FCC for the assignment round was intended to accomplish these objectives by concealing the information that can be misused by bidders to harm their opponents.

For any given region, assignment phase rules guaranteed a contiguous assignment to all winners. On the one hand, to minimize bidder’s participation costs, the auctioneer should accept bids only on assignment options that are consistent with assigning contiguous spectrum to all winners. For example, suppose that there are two winners in a given region who won 4 and 3 generic blocks respectively. Then the winner of 4 blocks should be presented with two assignment options: ABCD and DEFG. On the other hand, this bidder would be able to infer that there is only one other winner in this region who won 3 generic blocks. To conceal this information, the auctioneer can present a bidder with all assignment options that are consistent with contiguous assignments for this bidder only. In our example, the winner of 4 blocks would be presented with four assignment options: ABCD, BCDE, CDEF and DEFG. This policy still allows bidders to express all their tradeoffs among assignments for their own use, albeit somewhat increasing their participation costs since they are forced to evaluate infeasible options. Presenting the extra assignment options allows the auctioneer to obscure potentially sensitive information from bidders. For example, the winner of 4 blocks, when presented with four assignment options, cannot infer how many other winners there are (can be 1, 2, or even 3) or how many generic blocks each opponent won.

This innovation is probably not as critical in an auction with a core-selecting rule. However, in an auction with the VCG rule, where bidders can target their vulnerable opponents cheaply or even for free, this policy appears to be justified.

9. Conclusion

The recently-concluded FCC Incentive Auction is the newest “poster child” for game theory and market design improving social welfare. Buyers revealed their values to be at least $19.3 billion, while sellers revealed their costs to be at most $10 billion, indicating that the repurposing of 84 MHz of spectrum from television broadcasting to broadband wireless created substantial gains. Sellers may have been overbidding in the auction and buyers may have been underbidding, but such errors would go in the direction that strengthens our conclusion. Moreover, the ugly holdout problem among broadcasters appeared to have been insurmountable in the absence of an incentive-auction-like mechanism, making it unlikely that the repurposing of spectrum would have proceeded without it. In our view, it provides a compelling case study for the positive influence of market design.

Furthermore, the auction appears to have generated a number of external benefits that go beyond what can be inferred from auction data. Canada participated jointly with the US in the repacking of television stations; as a result, Canada also has a cleared 600 MHz band scheduled for auction. Both Mexico and Canada have adopted the band plan for 600 MHz spectrum, while Mexico and New Zealand have jointly proposed that the International Telecommunication Union adopt this band plan for harmonized use of the 600 MHz spectrum worldwide.

A number of other conclusions can also be drawn from a close examination of the Incentive Auction.

As a general message, the FCC Incentive Auction highlighted the importance of utilizing auction mechanisms that exhibit a great deal of robustness. The two biggest surprises in the auction were that Verizon submitted no bids whatsoever, while AT&T pulled the plug on its bidding after round 21 of stage 1. Our simulations in Section 5 indicate that, if the earlier AWS-3 Auction (FCC auction 97) had suffered similar levels of nonparticipation by the two largest US wireless providers, then its net revenues would likely have declined from $41.3 billion to $16.5 billion, a drop of 60%. The design of the Incentive Auction did not anticipate nonparticipation by Verizon and AT&T, but it did consciously try to make the mechanism as robust as possible against unexpected events and strategies. Ultimately, the mechanism performed well, despite the unexpected nonparticipation by the two largest wireless providers.

However, there was one significant element of the overall auction structure that was less robust and, in some scenarios, could have produced a less efficient outcome. The first component of the final stage rule required that the forward auction proceeds from Category 1 products in the top-40 PEAs reach an average price of $1.25 per MHz-pop. This component was not met in round 1 of stage 4, creating the real risk that the auction could have proceeded to stage 5 and cleared only six spectrum blocks. This would have reduced the elegance of the band plan in the US and diminished the likelihood that other countries would coordinate on the US band plan. As discussed above, part of the issue with the first component of the final stage rule is that it was an aggregate reserve price on a collection of spectrum blocks rather than an individual reserve price on each block. Moreover, the extended round feature was unlikely to correct this issue. The incentive auction mechanism would have been more robust without this aggregate reserve price feature; if a higher reserve price were desired, it would have been better to accomplish this by raising the individual opening (i.e., reserve) prices in the top-40 PEAs.

For spectrum auction practice going forward, the Incentive Auction offers a number of other lessons. As described above, there are two competing models for conducting sales of spectrum: the SMRA format, in which bidders name prices and every license is treated as a unique item that receives a separate bid; and a clock-based format with generic spectrum and an assignment round, in which the auctioneer names prices and bidders respond with the quantity of generic blocks that they desire. Prior to the Incentive Auction, the FCC had exclusively used the first approach, while regulators in Europe, Canada and Australia had experimented with the second model. However, its successful use in the Incentive Auction should create greater confidence in the second approach, and open the door to further applications by the FCC and other regulators. Indeed, the FCC is already considering a clock auction approach for its next auction: a reverse auction for the Connect America Fund Phase II Auction.[23]

The Incentive Auction's assignment phase provided a neat experiment on the choice of payment rule. Economists had put forward 15 years earlier the theoretical possibility of zero-revenue equilibria of the Vickrey auction when bidders' roles were complementary, but to our knowledge, this was the first instance in which zero-revenue equilibria have been observed and documented empirically. While there was a good justification for utilizing a VCG mechanism in this particular assignment phase, one lesson of the Incentive Auction is that a core-selecting mechanism is probably preferable whenever the regulator is indifferent to whether revenues accrue in the allocation phase or the assignment phase.

The Incentive Auction also points to the importance of competition policy in spectrum auctions. Prior to this auction, the distribution of sub-1-GHz spectrum in the US was skewed heavily toward the two largest wireless providers. The stated policy objective of the FCC in establishing the spectrum reserve was to prevent these two operators from foreclosing smaller firms from obtaining low-band spectrum. That the spectrum reserve turned out to be nonbinding does not prove that it was unnecessary. A more plausible interpretation is that the spectrum reserve was successful in making a foreclosure strategy impossible and in encouraging or emboldening participation by smaller bidders. Observe that 95% of spectrum (by value) was won by bidders that were reserve-eligible in all regions of the US. This development can be expected to enhance future competition in the wireless market.

The Incentive Auction also highlighted the principle that, in practical market design, the high-level economic rules are often more critical than the fine algorithmic detail. First, the key insight underlying the Incentive Auction was that it was politically unacceptable to cancel the license of the broadcaster on channel 48, but that it was politically acceptable to force this broadcaster to relocate to channel 24. Once enacted by Congress, this rule provided the underpinning for the successful repurposing of broadcast spectrum. Second, strategic supply reduction may have significantly increased the cost associated with all stages of the reverse auction. Rules to limit the exercise of supply reduction would likely have had a greater impact on auction performance than further algorithmic refinement.

We conclude on the note that the Incentive Auction is not only the newest "poster child" for game theory and market design, but it represents the shape of things to come. Economists' ambition to utilize auctions not only to allocate spectrum but to clear it of incumbents—or more broadly, to utilize market mechanisms not only for determining who gets to use spectrum but how it gets used—has been fulfilled successfully in an important setting. Other applications of this ambitious agenda now await.

[23] *Comment Sought on Competitive Bidding Procedures and Certain Program Requirements for the Connect America Phase II Auction (Auction 903)*, Public Notice, FCC 17-101 (Aug. 4, 2017) (*CAF II Auction Comment Public Notice*).

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Appendix A – Summary of Results

Table 4 shows the clearing cost and the forward auction proceeds for each stage of the Incentive Auction.

Table 4

Stage	Clearing Target	Licensed Spectrum	Clearing Cost	Gross Proceeds
1	126 MHz	100 MHz (10 blocks)	$86,422,558,704	$23,108,037,900
2	114 MHz	90 MHz (9 blocks)	$54,586,032,836	$21,519,907,210
3	108 MHz	80 MHz (8 blocks)	$40,313,164,425	$19,676,240,520
4	84 MHz	70 MHz (7 blocks)	$10,054,676,822	$19,632,506,746

After the assignment phase, the gross proceeds increased to $19,768,437,378.

Out of 62 bidders that were qualified by the FCC to bid in the auction, there were 50 winning bidders. Table 5 provides the winners with the largest commitments at the conclusion of the auction.

Table 5

Winner	Gross Commitment	Net Commitment (if different than gross)
T-Mobile	7,993,361,993	
Dish Network	6,211,154,496	
Comcast	1,724,877,376	
Columbia Capital	1,008,704,549	858,704,549
AT&T	910,202,302	
Bluewater	718,323,225	568,323,225
New Level	348,878,183	296,546,456
U.S. Cellular	328,661,977	

Appendix B – Further Details on the Forward Auction

B.1 Bidding options and bid types

In the clock phase, forward auction bidders were not provided the full flexibility of package bidding as that would have been inconsistent with the no excess supply rule and the goal of meeting the final stage rule. Bidders could use four different types of bids to express how they wanted the bidding system to handle a bid to change demand if that bid could not be applied in full, either because of the no excess supply rule or because of the eligibility restriction.

The four bid types were: simple bids, switch bids, all-or-nothing bids (AON), and all-or-nothing bids with backstopping (AON+). We find that simple bids and switch bids were used extensively, the use all-or-nothing bids was more limited, and the use of all-or-nothing bids with backstopping was extremely limited.

In addition to the four bid types, bidders were also given the option of intra-round bidding which allowed them to submit bids at any price in the product's price range for the round. A bidder could either submit a simple bid to maintain its demand from the previous round at the current round's clock price or request to change its demand at a price associated with the round (using any type of bid). We find that most bids were either at the highest or at the lowest price of the round, and that most of the bids at intermediate prices were bids to increase demand.

A total of 138,691 bids were submitted in the clock phase of the forward auction.[24] In the initial round (round 1 of stage 1), bidders submitted 724 bids to indicate their demands at the opening prices. In later rounds, bidders submitted 120,402 bids for maintaining demand at the round's clock price and 17,565 bids for changing demand (i.e., either increasing or reducing demand).

For a meaningful comparison of the frequency of each bid type, Table 6 only considers bids to change demand after the initial round. The table also indicates whether the bid price was the lowest in the round's price range for the product (that is, at the 0% price point), an intermediate price (strictly between the lowest and the highest), or the highest price for the product in the round (the product's clock price for the round, or equivalently at the 100% price point).

Table 6

Bids to Change Demand After Initial Round	Price			All Prices
	Lowest	Intermediate	Highest	
Simple	5,915	2,295	2,295	10,505
Switch	4,282	785	1,872	6,939
AON	67	7	39	113
AON+	1	7	0	8
Total	10,265	3,094	4,206	17,565

[24] The total number of bids (138,691) is smaller than the number of rows in the forward-bids file that is available on the FCC Public Reporting System (145,638), because each switch bid and each all-or-nothing bid with backstopping is represented by two rows in that file. In the numbers provided in this document, each bid is counted once.

Table 7 breaks down the bids to change demand into bids for increasing and reducing demand. Only simple and all-or-nothing bids are considered here, because by definition switch bids involve both a reduction and an increase whereas all-or-nothing bids with backstopping could only be placed for reductions in demand.

Table 7

	Bids to Reduce Demand	Bids to Increase Demand	Bids to Change Demand
Simple	6,631	3,874	10,505
AON	63	50	113

Simple Bids

A simple bid indicates a desired quantity for a product at a price. During bid processing, a simple bid was applied to the maximum extent possible subject to the no excess demand rule and the bidder's eligibility. For example, a simple bid to reduce a bidder's demand for a product from two blocks down to zero would be applied partially if there was only one unit of excess demand for the product.

Table 6 implies that 22% of all simple bids to change demand were at intermediate prices. However, the percentage of simple bids to reduce demand that were at intermediate prices is significantly lower. Table 8 provides a break-down between simple bids to reduce demand and simple bids to increase demand.

Table 8

Simple Bids[25] to:	Price			All Prices
	Lowest	Intermediate	Highest	
Reduce Demand	5,111	521	999	6,631
Increase Demand	804	1,774	1,296	3,874
Total	5,915	2,295	2,295	10,505

We observe that less than 8% of all simple bids to reduce demand were at intermediate prices (that is, with price points strictly between 0% and 100%). Furthermore, a lot of these bids were concentrated either around the lowest price or around the highest price for the round. In fact, only 112 (1.7%) of the simple bids to reduce demand had price points between 10% and 90%.

Intermediate prices were used more for bids to increase demand than for bids to reduce demand. The limited use of intra-round bidding for bids to reduce demand could be a consequence of the fact that the FCC used relatively low price increments to the set the clock prices of a new round.[26]

Bidders appear to have used intra-round bidding to prioritize bids to increase demand in the event that some of the bidder's reduction bids for the round could not be applied during bid processing. Since bids

[25] After the initial round.

[26] The price increment was 5% in most rounds. The FCC increased the price increment to 10% in the latter parts of stage 1 and stage 4.

were processed in increasing order of price point, a bidder could prioritize one bid to increase demand over another bid to increase demand by associating a lower price point with the first bid.

A significant number of the bids to increase demand at intermediate prices were placed by Dish (1,204 out of 1,774). For example, in round 1 of stage 3 Dish bid to reduce its demand for 9 products and to increase its demand for 348 other products. Three of the reduction bids were not applied during bid processing because of the no excess supply rule. Thus, it was not possible to apply all of Dish's bids for increasing demand because that would have caused Dish to exceed its eligibility. The auction system attempted to apply bids with higher priority (according to Dish's bids) first. As a result, 241 of Dish's bids to increase demand were applied and 107 were not applied.

Switch Bids

A switch bid is a request to move demand for up to n blocks in a given PEA from one category to another category. Thus, a switch bid could have been used in stages 1-3 to move demand from Category 1 to Category 2 (e.g., if the price for Category 1 was much higher than the price for Category 2) or from Category 2 to Category 1 (e.g., if the gap between the two prices was reduced in the previous round). Similarly, after the final stage was met and the reverse split was implemented, a switch bid could be used to request to move demand from the unreserved product to the reserved or vice versa.

A switch bid ensures that the bidder's total demand in the PEA remains the same. For example, if the bidder requested to switch one block from the unreserved to the reserved category but there was no excess demand for the unreserved product, the switch bid would not be applied and the bidder's demand would not change for either of these products.

If switch bids had not been available, in order to move its demand from an unreserved product to the reserved the bidder would submit two separate simple bids: one to reduce demand for the unreserved and one to increase demand for the reserved. Even if the reduction bid could not be applied because of the no excess supply rule, it could be plausible (depending on the bidder's eligibility and on what other bids it submitted in the round) that the bid to increase demand for the reserved product could be applied. In that case, the bidder's total demand in the PEA would increase. Switch bids eliminate this risk by linking the bid to increase demand for one category with the bid to reduce demand for the other category.

No switch bids were placed in stages 1-3. This was likely a consequence of the fact that the number of Category 2 products in stages 1-3 was very limited, and that bidders strategically used Category 2 products to park eligibility.

All the switch bids in the auction were made after the reserve split, that is, starting in round 3 of stage 4. Out of the 6,939 switch bids, 3,825 were requesting to move demand from the reserved to the unreserved product and 3,114 were requesting to move demand from the unreserved to the reserved product.

Some of the bidders expressed a clear preference for unreserved products, presumably because the reserved products were associated with certain restrictions. For instance, all of the switch bids submitted by Columbia Capital were to move demand from the reserved to the unreserved product. However, most bidders submitted switch bids in both directions, depending on the relative prices of the reserved and the unreserved products in a PEA.

All-or-nothing Bids

All-or-nothing bids indicate a desired quantity of a product at a price, just like simple bids. However, all-or-nothing bids were either applied in full or not at all. These bids were available for a bidder that did not wish to place bids that could be applied partially. If an all-or-nothing bid to reduce demand could not be applied, the bidder would still hold its unreduced quantity potentially at a higher price.

As shown in Table 7, out of a total of 113 all-or-nothing bids 63 were for reducing demand and 50 were for increasing demand. The majority of all-or-nothing bids were submitted by AT&T and Spectrum Financial Partners. Only seven all-or-nothing bids were submitted by other bidders.

An intended use case for all-or-nothing bids was to allow a bidder to avoid holding one block when requesting to reduce its demand from two to zero blocks. There were 642 bids (all-or-nothing and simple) to reduce demand from two to zero blocks. 60 of these were all-or-nothing bids. 56 of these bids were by AT&T, three by Mark Twain Communications, and one by Financial Spectrum Partners. Thus, with the exception of AT&T, bidders hardly used all-or-nothing bids with the intention to avoid the possibility of holding one block after the round when submitting a bid to reduce demand from two to zero.

All-or-nothing bids were also used to manage eligibility. For example, in round 23 of stage 1, Chariton Valley Telephone Corporation submitted an all-or-nothing bid to reduce its demand in PEA 393 from five blocks to one block. This bid might appear counterintuitive at first, because one might expect that the bidder would try to avoid holding a quantity of one block. But in the same round, the bidder submitted a simple bid to increase PEA 180 by 1 unit. PEA 393 has 25 bidding units and PEA 180 has 100 bidding units. By submitting these bids the bidder ensured that a reduction in PEA 393 would be applied if and only if the reduction could be equal to 4 blocks in which case the increase in PEA 393 could be applied. If the bidder had submitted a simple bid for the reduction of 4 blocks, there would be a risk that the reduction bid would be applied only partially (not freeing up enough bidding units to apply the increase in PEA 180) in which case the bidder's eligibility would be reduced after the round.

All-or-nothing Bids with Backstopping

By submitting an all-or-nothing bid to reduce demand the bidder could ensure that it would not hold an undesirable quantity after the round, but the bidder could continue to hold the same (unreduced) demand at a higher price. An all-or-nothing bid with backstopping allowed the bidder to backstop the all-or-nothing bid at a higher price. Thus, if the price reached the specified backstop price, the bid would be applied in part (like a simple bid for the same quantity).

There were only 8 all-or-nothing bids with backstopping. 7 of these bids were submitted by the same bidder (Gold Spectrum, LLC) and were essentially the same bid repeated in four rounds. The backstop price of each of these bids was $1 higher than the all-or-nothing price. This implies that these all-or-nothing bids with backstopping had essentially the same effect as a simple bid at that price. We conclude that the use of all-or-nothing bids with backstopping was extremely limited.

The Absence of the Ability to Switch across Products (or PEAs)

In 2012, the FCC released the Incentive Auction Notice of Proposed Rulemaking, which included a high-level description of the proposed auction design in Appendix C (Milgrom, et al., 2012). That proposal had suggested that a bidder could specify a demand decrease for one product and a demand increase for another product (presumably in a different PEA) with the same bid, and that a bid could also involve multiple products or quantities.

The ability to submit switch bids involving products from different PEAs was not provided to bidders in the Incentive Auction, presumably on grounds of simplicity. That is, switch bids could only involve products in the same PEA. This had the potential of providing less flexibility to bidders. For instance, a bidder that wanted to reduce its demand by one block in each of two smaller PEAs in order to increase its demand by one block in a larger PEA would have to do so using only simple bids, and potentially lose some eligibility unintentionally if one of the two reduction bids could not be applied because of the no excess supply rule.

To find the extent to which bidders unintentionally lost eligibility (which they could have avoided if switch bids across products had been available), we look at all the times that a bidder's eligibility was reduced even though the bidder submitted activity that met or exceeded the required activity to maintain eligibility. There were only 18 such instances, and the reduction in the bidder's eligibility was less than 20% in each of these instances.[27] This suggests that the absence of the ability to submit switch bids across products was generally not harmful for bidders.

B.2 Strategic Bidding – Parking Eligibility

Parking Eligibility in Top PEAs

In the first rounds of stage 1, the aggregate demand for some of the top PEAs, such as New York (PEA001) and Los Angeles (PEA002), was extremely high, indicating that bidders were parking their eligibility. For example, in the initial round, two of the bidders bid for 10 blocks in New York (PEA001) each, a significantly larger quantity than any bidder was expected to be interested in.

We next provide some evidence that bidders were not expressing their true demands in stage 1 by considering the bidding behavior in Los Angeles (PEA002). In stage 1, the supply for Los Angeles was equal to 5 blocks. In round 25 of stage 1, bidders indicated aggregate demand for 8 blocks at the clock price of $388,489,000. However, in the following rounds of stage 1, bidders requested only 4 blocks in aggregate at the same price ($388,489,000). Because of the no excess supply rule, the aggregate processed demand remained at 5 blocks (that is, equal to the supply for stage 1). In later stages, the supply of blocks in Los Angeles increased due to an international agreement with Mexico. During stage 4, the aggregate demand for Los Angeles increased to 6 blocks; however, the supply was equal to 7 and, as a result, there was one unsold block in Los Angeles even though the final clock price in Los Angeles was $388,489,000 (that is, the price did not increase since round 25 of stage 1).

The information provided in Table 9 also suggests that bidders were parking eligibility during stage 1. The table shows, for each of the six largest winners in the auction, the number of PEAs bid in the initial round, the number of PEAs bid in round 20 of stage 1 (i.e., just before AT&T reversed its strategy), and the number of PEAs where the bidder had winnings.

[27] A bidder's eligibility was reduced by more than 10% in only 3 of these instances, and by more than 5% in only 6 of these instances.

Table 9

Bidder	Number of PEAs Bid in Initial Round	Number of PEAs Bid in Round 20 of Stage 1	Number of PEAs with Winnings
T-Mobile	409	409	414
Dish	54	59	416
Comcast	6	38	72
Columbia Capital	3	3	6
AT&T	13	67	18
Bluewater	3	66	64

With the exception of T-Mobile, the ratio of the number of PEAs bid by the bidder in the initial round over the number of PEAs where the bidder won blocks is generally small for these bidders. This suggests that most of these bidders were attempting to park eligibility early in the auction without revealing their true preferences.

However, this strategy was risky. Even though the final stage rule was not met in stage 1 (as expected), the aggregate demand in New York could only be reduced by one block at the beginning of a new stage, because the supply of blocks in New York was reduced by one block and the no excess supply rule implied that aggregate demand could not be reduced below supply. When stage 1 ended, multiple bidders were holding more blocks in New York than they were interested in and tried to reduce demand at the beginning of every new stage. Some of the bids could not be applied[28] and, as a result, one of the bidders appears to have won more blocks in New York than it wanted.

Parking Eligibility in Category 2 Products

Category 2 blocks were blocks with an impairment level between 15% and 50%. Because the impairment level of the Category 2 blocks offered in a given PEA could vary significantly from one stage to the next (e.g. it could be 16% in stage 1 and 45% in stage 2), the FCC decided to not apply the no excess supply rule for Category 2 products at the beginning of a new stage. That is, a bid to reduce demand for a Category 2 product would be applied in full during the bid processing of the first round of a new stage, even if there were no excess demand for that product.

However, the reverse auction cost in stage 1 was so high that bidders expected that stage 1 would not be the final stage. Some of the bidders then realized that they could park some eligibility in Category 2 products with the intention of using that eligibility elsewhere in a later stage. The extent of parking in Category 2 blocks was limited though, because only a small number of Category 2 blocks was available and the number of bidding units associated with those products was not significant.

Bidders also parked some eligibility in Category 2 blocks during stage 2 and stage 3. However, this was even more limited than in stage 1, because the number of Category 2 blocks available was even smaller.

[28] Because these reduction bids were at the 0% price point, the auction system used pseudorandom numbers to select which bid to apply.