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ABSTRACT

We explore the sensitivity of the U.S. government's ongoing incentive auction to multi-license ownership by broadcasters. We document significant broadcast TV license purchases by private equity firms prior to the auction and perform a prospective analysis of the effect of ownership concentration on auction outcomes. We find that multi-license holders are able to raise spectrum acquisition costs by 22% by strategically withholding some of their licenses to increase the price for their remaining licenses. We analyze a potential rule change that reduces the distortion in payouts to license holders by up to 80%, but find that lower participation could greatly increase payouts and exacerbate strategic effects.

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1 Introduction

In 2010, the U.S. Federal Communications Commission (FCC) proposed to acquire spectrum from broadcast TV license holders and sell it to wireless carriers to be repurposed into mobile broadband spectrum. The so-called incentive auction combines a reverse auction for broadcast TV licenses with a forward auction for selling the thus-acquired spectrum to wireless carriers. Between the two auctions lies a repacking process where remaining broadcasters are reassigned channels to clear a contiguous nationwide block of spectrum for wireless use. Prior to the currently ongoing auction, estimates put the expected revenue from the forward auction at up to $45 billion, in excess of the payouts to broadcast TV license holders in the reverse auction, with the balance going towards the costs of repacking spectrum into a contiguous block and to the government.[1,2] In this paper, we study the potential for strategic behavior in the reverse auction.

We document that following the announcement of the incentive auction, a number of private equity firms acquired broadcast TV licenses in several local media markets, often purchasing multiple licenses in the same market. Newspaper articles and industry reports claimed that these purchases were undertaken with the goal of trying to "flip" broadcast TV licenses for profit in the reverse auction.[3] Politicians also raised concerns about speculation.[4] Yet, reselling broadcast TV licenses does not necessarily entail efficiency losses.

We argue that in addition to speculative motivations behind reselling broadcast TV licenses, there is the potential for strategic bidding. In a prospective analysis of the incentive auction, we show that owners of multiple licenses have an incentive to withhold some of their licenses from the auction, thereby driving up the closing price for the remaining licenses they own and affecting a large transfer of wealth from the government - and ultimately taxpayers - to themselves. Apart from affecting closing prices, this behavior causes efficiency losses as the set of broadcast TV licenses surrendered in the auction is not the socially optimal set and may reduce the total amount of spectrum that will be repurposed.

Repurposing spectrum from broadcast TV to mobile broadband usage is no doubt an extremely valuable - and complex - undertaking. The incentive auction was very carefully designed and has many desirable properties such as strategy proofness (Milgrom et al., 2012; Milgrom and Segal, 2014). If broadcast TV licenses were separately owned, then it is optimal for an owner to bid a

[1]See Expanding Opportunities for Broadcasters Coalition (EOBC) Notice of Oral Ex Parte Filing with the FCC, June 13, 2014, available at http://www.tvtechnology.com/portals/0/EOBC0614.pdf, accessed on November 15, 2015.

[2]The Congressional Budget Office (CBO) estimates the net proceeds from the incentive auction to fall between $10 billion and $40 billion, with an expected value of $25 billion, the middle of that range. "Proceeds From Auctions Held by the Federal Communications Commission", CBO Report 50128, April 21, 2015, available at https://www.cbo.gov/publication/50128, accessed on November 15, 2015.

[3]See "NRJ Wins Bidding For WSAH New York," TVNewsCheck, November 29, 2011, "Small TV Stations Get Hot," The Wall Street Journal, September 3, 2012, "Speculators Betting Big on FCC TV Spectrum Auctions," Current.org, February 26, 2013, "TV Spectrum Speculation Nears $345 Million," TVNewsCheck, March 1, 2013, "Broadcast Incentive Spectrum Auctions: Gauging Supply and Demand," SNL Kagan Broadcast Investor, November 20, 2013, and "TV Station Spectrum Deals Expand Into Major Network Affiliates as Players Stake Out Positions Pre-Auction," SNL Kagan Broadcast Investor, December 4, 2013.

[4]See "Rep. LoBiondo Seeks FCC Info On Possible Spectrum Speculation," Broadcasting & Cable, February 12, 2014.

station's value as a going concern in exchange for relinquishing the broadcast license; we refer to this as naive bidding. Our paper points out the sensitivity of the incentive auction to multi-license ownership. In particular, the rules of the auction leave room for strategic supply reduction for firms that own multiple broadcast TV licenses. Such firms can withhold a subset of their licenses from the auction to raise the closing price for the remaining licenses. This behavior is purely rent-seeking, as these firms are attempting to increase their share of existing wealth without creating any new wealth.

We use a simple model to illustrate how strategic supply reduction works in the context of the reverse auction and under what circumstances it is a profitable strategy for multi-license owners. Our model implies that certain types of broadcast licenses are more suitable for a supply reduction strategy and that certain types of local media markets are more vulnerable to this type of behavior. We begin by showing that the ownership patterns in the data are broadly consistent with the implications of the model.

In a second step, we analyze the reverse auction in more detail and quantify increased payouts and efficiency losses due to strategic supply reduction. To do so, we undertake a large scale valuation exercise to estimate reservation values for all currently held UHF broadcast TV licenses. We combine various data sources to estimate a TV station's cash flows and from them infer its value as a going concern. This allows us to simulate the auction outcome for all participating license holders, accounting for the repacking process at a regional level, and then to assess the impact of potential strategic bidding.

We compare the outcome under naive bidding with the outcome when we account for the ownership patterns in the data and allow multi-license owners to engage in strategic supply reduction. Our approach solves for all equilibria of a simplified version of the reverse auction that accounts for the repacking process at the regional - though not at the national - level. We then show that across markets, strategic supply reduction has a large impact on closing prices and payouts to broadcast TV license holders and causes sizable efficiency losses. For a nationwide clearing target of repurposing 126 MHz of spectrum, the initial starting point of the incentive auction when it commenced on March 29, 2016, strategic behavior by multi-license owners increases payouts by 22%. The payout increases, as well as payouts from the auction in general, are concentrated in a small number of markets, however, with nearly 99% of payout increases occurring in markets with two or more owners of multiple licenses. This reflects two factors. First, there is significant variation in station cashflows and thus willingness-to-sell due to stations' differential success in attracting advertising revenue. This results in steep increases in closing prices as more licenses are acquired. Second, the FCC's need to clear spectrum is particularly pronounced in large markets where the expected demand by wireless carriers means that even high-value TV licenses can successfully sell into the auction and that strategically withholding a low-value station can drive up closing prices significantly. We illustrate these issues in a case study of the Philadelphia, PA, market.

Netting out the firms' reservation values from their auction payouts, the strategic supply reduction strategy translates into surplus increases of several billion dollars across broadcast TV license owners. This reflects that a multi-license owner who withholds a license from the auction creates a positive externality for other market participants by raising the closing price in the market. The multi-license owner, by selling his remaining licenses in the market, captures some of this externality, but not all of it: while in aggregate, payouts increase by 22%, they increase by 25% for multi-license owners and 19% for single-license owners.

We analyze a potential rule change that imposes a constraint on the ordering of bids of multi-license owners. The rule change reduces the effect of strategic behavior by roughly eighty percent. This result is directly policy relevant as it suggests ways of mitigating the impact of strategic supply reduction. Our hope is that this proves useful in designing future auctions in the U.S. and other countries as they strive to alleviate the "spectrum crunch" resulting from the rapid growth in data usage by smartphones in recent years.

We also illustrate how a firm may extend a supply reduction strategy by leveraging technological constraints on the repacking of spectrum across local media markets. While a complete analysis of multi-market strategies at the national level is computationally infeasible, we highlight a particular case of a firm owning licenses in adjacent markets and the potential effect of reducing supply in one market on the closing price in another targeted market. In this case, we find a six-fold increase in the impact of strategic bidding.

Finally, we quantify the effect of potential low participation by non-commercial (public) and religious broadcasters. A reduction in participation among such licenses leads to a significant number of auction failures, and large increases in payouts when auctions complete. We suggest that modifying must-carry regulations could be a useful tool in increasing auction participation.

There is a rich literature on strategic bidding in multi-unit auctions. Substantial theoretical work (Wilson, 1979; Back and Zender, 1993; Menezes, 1996; Engelbrecht-Wiggans and Kahn, 1998; Jun and Wolfstetter, 2004; Riedel and Wolfstetter, 2006; Ausubel et al., 2014) and experimental evidence (List and Lucking-Reiley, 2000; Kagel and Levin, 2001; Engelmann and Grimm, 2009; Goeree, Offerman and Sloof, 2013) point to the potential for strategic demand reduction. In addition, case studies of past spectrum auctions have documented strategic demand reduction (Weber, 1997; Grimm, Riedel and Wolfstetter, 2003). Our paper is most closely related to the empirical literature examining market power in wholesale electricity markets (Wolfram, 1998; Borenstein, Bushnell and Wolak, 2002; Hortacsu and Puller, 2008), where firms bid supply schedules and have strategic incentives to alter their bids and raise closing prices for inframarginal units. In contrast to electricity markets, however, in our setting the acquisition of significant market power is easier: a small number of licenses outstanding in a given local market, combined with the discreteness of broadcast spectrum units (6 MHz), implies that a single additional license can confer a significant increase in market power in the spectrum market to its owner.

Significantly, our paper departs from much of the auction literature in that it does not invert the first-order conditions to recover valuations from observed bids. Instead, we use auxiliary data to directly estimate valuations. One reason is the lack of bidding data because, by congressional order, the FCC is unable to release details of the auction proceedings until two years after completion of the incentive auction.

However, even if data were available, extending the standard first-order conditions approach to our case of multi-unit auctions with personalized prices is less than straightforward and may entail challenges to identification as discussed by Cantillon and Pesendorfer (2007) in the context of heterogeneous multi-unit first-price auctions. More importantly, the descending clock nature of the ongoing incentive auction exacerbates identification concerns. While the value of a broadcast license can be inferred from the price at which it drops out of the auction, payout price provides at most an upper bound on the value of a broadcast license that instead sells into the auction. Further, observing that a broadcast license is withheld from the auction is uninformative about its value if a multi-license owner chooses to withhold it from the auction for strategic reasons. This is in contrast to work on wholesale electricity markets where complete supply schedules are observed. We also do not adopt the moment inequalities approach in Fox and Bajari (2013) that - rather than assuming full optimality of bids - only assumes that the configuration of licenses that a multi-license owner sells into the auction dominates any alternative configuration due to the typically small number of alternatives in our setting given that licenses are not perfect substitutes for one another. This approach also only identifies relative valuations but not the levels of valuations that are required for the analysis of welfare effects of ownership concentration.

Our work is also related to the extensive literature on collusion in auctions (Asker 2010, Conley and Decarolis 2016, Kawai and Nakabayashi 2015, and Porter and Zona 1993, among others), including spectrum auctions (Cramton and Schwartz, 2002). A multi-license owner in our setting internalizes the profit implications of all licenses he controls as is the case with colluding, but otherwise independent, single-license owners. Finally, we contribute to the literature on distortions induced by incentive schemes and regulation in various settings such as employee compensation (Oyer, 1998), environmental regulation (Fowlie, 2009; Bushnell and Wolfram, 2012), health care (Duggan and Scott Morton, 2006), and tax avoidance (Goolsbee, 2000).

The remainder of this paper is organized as follows: Section 2 describes the setting and sets out a simple model of strategic supply reduction, Section 3 presents data and descriptive evidence, Sections 4 and 5 describe the main analysis and results, and Section 6 concludes.

2 The FCC incentive auction

The rapid growth in data usage by smartphones has significantly increased the demand for mobile broadband spectrum in recent years.[5] At the same time, some previously allotted spectrum is no longer used intensively. In particular, each of approximately 8,500 currently operating TV stations

[5] According to FCC Chairman Tom Wheeler, "America has gone mobile. Most Americans would have a hard time imagining life without their smartphones, and tens of millions are similarly in love with their tablets. The problem is that spectrum, the lifeblood of all wireless technologies, is finite. That wasn't a problem before the mobile web, when most consumers were mostly watching videos or surfing the web at home. If we don't free up more airwaves for mobile broadband, demand for spectrum will eventually exceed the supply. If you've ever been frustrated by websites that loaded slowly or videos that wouldn't download to your phone, you have a sense what that world could look like." See "Channel Sharing: A New Opportunity for Broadcasters," Official FCC Blog, available at https://www.fcc.gov/news-events/blog/2014/02/11/channel-sharing-new-opportunity-broadcasters, accessed on November 15, 2015.

owns a license for a 6 MHz block of spectrum covering a particular geographical area for over-the-air transmission of programming. Yet, as of 2010 only about 10% of U.S. TV households used broadcast TV, with a rapidly declining trend.[6]

In its 2010 National Broadband Plan, the FCC under then-chairman Julius Genachowski proposed, and was authorized by Congress in 2012, to conduct an incentive auction to reallocate spectrum from TV stations located in the higher frequency UHF band to wireless providers. The incentive auction consists of a reverse auction in which TV stations submit bids to relinquish spectrum rights in exchange for payment and a forward auction in which wireless operators bid for the newly available spectrum.

While the FCC has conducted spectrum auctions in the past, the incentive auction is the first time an auction to sell spectrum is combined with an auction to purchase spectrum from existing licensees.[7] Designing this auction is complicated not only by incumbent claims on spectrum, but also by technological constraints for mobile data and broadcast TV uses. Originally projected for early 2014, the incentive auction was repeatedly postponed due to legal and technological challenges, first to the middle of 2015 and then again to its ultimate starting date of March 29, 2016.[8]

The format of the ongoing auction was made public in May 2014.[9] The forward auction to sell spectrum to wireless carriers uses an ascending-clock format similar to previous spectrum auctions. The reverse auction uses a descending-clock format in which the price offered to a TV station for its spectrum usage rights declines with each successive round of bidding. A TV station faces a price for its broadcast license that is personalized to it (see Section 2.2 for details). If a TV station chooses to participate in the reverse auction, it has several options for relinquishing its spectrum usage rights: going off the air, moving channels from a higher frequency band (UHF channels 14-36 and 38-51 or high VHF channels 7-13) to a lower frequency band (respectively, VHF channels 2-13 or low VHF channels 2-6) to free up more desirable parts of the spectrum, or sharing a channel with another TV station.

Between the reverse and forward auctions, a repacking process takes place in which the remaining TV stations are consolidated in the lower end of the UHF band to create a contiguous block of

[6] "Connecting America: The National Broadband Plan", FCC, 2010, Chapter 5, p. 89.

[7] "Let's start with the concept of an incentive auction. While it has never been tried before, its power lies in how it addresses the root of all issues: economics. If it is possible to marry the economics of demand with the economics of current spectrum holders, it should be possible to allow market forces to determine the highest and best use of spectrum. In mid-2015 we will run the first ever incentive auction. Television broadcasters will have the opportunity to bid in a reverse auction to relinquish some or all of their spectrum rights, and wireless providers will bid in a forward auction on nationwide, 'repacked' spectrum suitable for two-way wireless broadband services." See FCC Chairman Tom Wheeler's prepared remarks at the "Wireless Spectrum And The Future Of Technology Innovation" Forum, available at https://apps.fcc.gov/edocs_public/attachmatch/DOC-326215A1.pdf, accessed on November 15, 2015.

[8] See "The Path to a Successful Incentive Auction," Official FCC Blog, December 6, 2013, available at https://www.fcc.gov/news-events/blog/2013/12/06/path-successful-incentive-auction-0, accessed on November 15, 2015, and "F.C.C. Delays Auction of TV Airways for Mobile," The New York Times, October 24, 2014.

[9] See https://apps.fcc.gov/edocs_public/attachmatch/FCC-14-50A1.pdf, accessed on November 15, 2015. An excellent and detailed explanation of the mechanism is available from the FCC and greatly informs our analysis. See Appendix D of FCC Public Notice in matter FCC-14-191 "Comment Sought On Competitive Bidding Procedures For Broadcast Incentive Auction 1000, Including Auctions 1001 And 1002," released December 17, 2014.

spectrum in the higher end of the UHF band for wireless use.[10] The process is visually similar to defragmenting a hard drive on a personal computer. However, it is far more complex because many pairs of TV stations cannot be located on adjacent channels, even across markets, without causing unacceptable levels of interference. As a result, the repacking process ties together all local media markets. In practice, the reverse auction is therefore at the national level. A further consequence of interference is that even though each TV station owns a license for a 6 MHz block of spectrum covering a particular geographical area, far more than $6n$ MHz of spectrum are likely required to accommodate n remaining TV stations in a market.

The auction rules integrate the reverse and forward auctions in a series of stages. For the first stage, initial commitments from stations and repacking constraints determined an initial maximum nationwide clearing target of 126 MHz. Each stage of the incentive auction begins with multiple rounds of the reverse auction, followed by multiple rounds of the forward auction. The reverse auction determines the cost of acquiring a set of licenses that allow the repacking process to meet the clearing target. There are many different feasible sets of licenses that could be surrendered to meet a particular clearing target given the complex interference patterns between stations; the reverse auction is intended to identify the low-cost set.

After the reverse auction determines the cost of acquiring an amount of spectrum, the forward auction determines the willingness-to-pay of wireless operators for this amount of spectrum. If willingness-to-sell in the reverse auction outpaces willingness-to-pay in the forward auction, the clearing target is decreased, so that a smaller set of lower value TV stations have to be acquired. The process repeats until a "final stage rule" is satisfied that ensures that proceeds in the forward auction (more than) cover payouts in the reverse auction and the cost of repacking spectrum.[11]

At the time of this writing, the FCC has completed three stages of the auction. The reverse auction phase of the auction's first stage concluded on June 29, 2016. The total payout required to meet the initial 126 MHz clearing target amounted to $86.4 billion, which was not met in the forward auction in attempting to sell the freed spectrum to wireless providers; it yielded a payout of only $23.1 billion. Since this first stage, the clearing target has been lowered twice and the FCC opened the fourth stage for a clearing target of 84 MHz on December 13, 2016.

We next provide additional details on the reverse auction and illustrate the potential for strategic supply reduction.

2.1 The reverse auction

The reverse auction uses a descending-clock format. A TV station that participates in the reverse auction is offered a personalized price at which it can either remain in the auction, indicating that

[10] Congress' authorization of the incentive auction required the FCC to make all reasonable efforts to preserve the coverage area and population served by TV stations involved in the repacking.

[11] Specifically, the final stage rule requires that proceeds in the forward auction are at least $1.25 per MHz per population for the largest 40 wireless service market areas and not only cover payouts in the reverse auction but also the FCC's administrative costs, the reimbursements of channel relocation costs incurred by TV stations, and the funding of the First Responder Network Authority's public safety operations.

it is prepared to accept this price to cease operating and surrender its broadcast license, or leave the auction, indicating that the price is too low and that it prefers to continue operating and potentially be repacked to a new UHF channel. In the subsequent analysis, we abstract from the options to relocate from a higher to a lower frequency band or to share a channel with another station. We discuss this simplification further in Section 4.2.

Broadcast licenses are assigned by the FCC to a local media market, which is the designated market area (DMA) as defined by Nielsen Media Research based on the reach and viewing patterns of TV stations. A DMA is defined as a group of counties such that the home market TV stations hold a dominance of total hours viewed. There are 210 DMAs in the U.S. that vary in size from New York, NY, with over 7 million TV households, to Glendive, MT, with 4,230 TV households. Appendix Table 12 lists the top ten DMAs based on their 2012 rank.

Across these 210 markets, a total of 2,166 broadcast licenses are eligible for the auction.[12] They can be classified by type of service into UHF and VHF stations, by type of use into commercial and non-commercial stations, and by power output into full-power (primary and satellite[13]) and low-power (class-A) stations. Appendix Table 13 summarizes the auction-eligible broadcast licenses.

Formally, in round τ of the reverse auction, a currently active TV station j is offered the price

$$p_{j\tau} = \varphi_j P_\tau,$$

where P_τ is the base clock price and φ_j is the station's broadcast volume. The base clock price P_τ begins at \$900 and decreases with each successive round of bidding. The broadcast volume

$$\varphi_j = M\sqrt{CoveragePop_j \cdot InterferenceCnt_j} \tag{1}$$

is a known function of the station's population reach $CoveragePop_j$ and the interference count $InterferenceCnt_j$, defined as the number of TV stations that station j can potentially interfere with in the repacking process. Finally, $M = 17.253$ is a scaling factor that is chosen to set the maximum φ_j across the U.S. to one million.

The broadcast volume is an important concept: the FCC uses it to personalize the base clock price to a TV station based on its value as a broadcast business (as proxied by population reach) and the difficulty of repacking the station in case it does not surrender its license (as proxied by the interference count). The broadcast volume thus reflects that the FCC is willing to incentivize a TV station to surrender its license if the alternative of having to repack the station is particularly challenging. Importantly, the broadcast volume for all TV stations is known in advance to all auction participants.

The design of the reverse auction is partly dictated by the FCC's obligation to guarantee a 6

[12]See http://www.fcc.gov/learn, accessed on November 15, 2015. The FCC excludes approximately 10,000 low-power, translator, multi-cast signal, and cable stations from the reverse auction. In 2016, the FCC updated the list of auction-eligible stations, see http://transition.fcc.gov/Daily_Releases/Daily_Business/2015/db0609/DA-15-679A2.pdf, accessed on February 10, 2016. In this paper, we work with the earlier list of 2,166 auction-eligible stations as it underlies the FCC's repacking simulations (see Section 3.1).

[13]A satellite station is a relay station that repeats the broadcast signal of its parent primary station.

MHz block of spectrum to any TV station that chooses to remain on air rather than surrender its license. At the initial base clock price of \$900, most, if not all, TV stations would be prepared to surrender their licenses. Hence, any remaining TV stations can be trivially repacked. The auction mechanism then preserves the feasibility of repacking as it unfolds as follows: as the base clock price descends, licenses withdraw from the auction, deciding that the price is too low and that they would prefer to continue broadcasting. When this happens, the feasibility of repacking every single remaining license in the auction must be asserted one-by-one given the interference patterns of the withdrawing and the remaining stations. If a remaining license can no longer be repacked, the price it sees is "frozen" and it is declared to be "provisionally winning," in that the FCC will accept its bid to surrender its license. In this case, the withdrawing station effectively sets the price of the frozen station. The base clock price then falls and the process of feasibility checking repeats with each new withdrawal. The reverse auctions ends if all TV stations have either withdrawn from the auction or are provisionally winning. Note that there is no single market price at which a station sells; different stations obtain different closing prices for their spectrum depending on the exact base clock price when, given the implied set of withdrawn stations, they could no longer be repacked.

2.2 Strategic supply reduction

Clock auctions are strategy proof (Milgrom et al., 2012; Milgrom and Segal, 2014). Hence, if a TV station is independently owned, its owner optimally remains in the reverse auction until

$$p_{j\tau} = \varphi_j P_\tau < v_j,$$

where v_j is the reservation value of TV station j that reflects its value as a going concern. We henceforth refer to this strategy as naive bidding.

Clock auctions are not only strategy proof but also "group-strategy proof" (Milgrom and Segal, 2014). This means that no coalition of bidders has a joint deviation from naive bidding that is strictly profitable for all members of the coalition. However, as Milgrom and Segal (2014) explicitly acknowledge, their results do not apply if bidders are "multi minded," a concept that includes bidders with multiple objects for sale.

We show that a firm owning multiple broadcast licenses may indeed have an incentive to deviate from naive bidding. Note that this does not contradict group-strategy proofness as it suffices that the deviating group, i.e., the multi-license owner, is better off as a whole. Withdrawing a license from the auction could increase the price for the remaining broadcast TV licenses that a firm owns. However, the firm is then left with a TV station that it may have been able to sell into the auction. Therefore, this supply reduction strategy is only profitable if the gain from raising the closing price for other stations exceeds the loss from continuing to own a TV station instead of selling it into the auction.

For concreteness and simplicity, consider a situation where all stations are perfectly interchangeable in the repacking process. A firm owns TV stations a and b. The FCC intends to acquire k broadcast licenses and stations are ordered in ascending order of the ratio $\frac{v_j}{\varphi_j}$. If $\frac{v_a}{\varphi_a} < \frac{v_k}{\varphi_k}$ and $\frac{v_b}{\varphi_b} < \frac{v_k}{\varphi_k}$, then under naive bidding the reverse auction closes at base clock price $\frac{v_{k+1}}{\varphi_{k+1}}$ and both licenses sell into the auction, yielding the firm a profit of $(\varphi_a + \varphi_b)\left(\frac{v_{k+1}}{\varphi_{k+1}}\right) - (v_a + v_b)$. On the other hand, if the firm withholds station a from the auction, then the closing base clock price rises to $\frac{v_{k+2}}{\varphi_{k+2}}$ and its profit is $v_a + \varphi_b \frac{v_{k+2}}{\varphi_{k+2}} - v_b$. It is therefore profitable to engage in strategic supply reduction and withhold TV station a from the auction if the gain in profit from selling the license of TV station b outweighs the loss in profit from not selling the license of TV station a, or

$$\varphi_b \left(\frac{v_{k+2}}{\varphi_{k+2}} - \frac{v_{k+1}}{\varphi_{k+1}}\right) > \varphi_a \left(\frac{v_{k+1}}{\varphi_{k+1}}\right) - v_a. \tag{2}$$

The left-hand side implies that strategic supply reduction is more likely to be profitable if φ_b is large and if the increase in the closing base clock price $\frac{v_{k+2}}{\varphi_{k+2}} - \frac{v_{k+1}}{\varphi_{k+1}}$ is large. The right-hand side implies that it is more likely to be profitable if φ_a is small and v_a is large. In short, strategic supply reduction is more likely to be profitable if the "leverage" of increasing the closing base clock price is large and the opportunity cost of continuing to own a TV station is small.

Strategic supply reduction has been explored in earlier work on multi-unit auctions in wholesale electricity markets (e.g. Wolfram, 1998): if a firm's bid for one of its generators has a chance to set the price, then the firm has an incentive to raise that bid if it will earn the price increases on its inframarginal generators.[14] Other electricity market papers consider this the exercise of market power, and note that the effects can be large when demand or supply is inelastic (Borenstein, Bushnell and Wolak, 2002). Unlike in wholesale electricity, a broadcast TV license is indivisible, leading to sharper behavior in our setting: while there is a maximum of 28 UHF licenses outstanding in a given DMA market, the median DMA market has 7 UHF licenses, and the mean is 8.2; for the median market, the market share increase from owning two licenses, rather than a single one, represents a market share jump from 14.3% to 28.6%. Furthermore, because of interference constraints, licenses are not homogeneous in the repacking process. Both facts may amplify the impact of strategic supply reduction. At the same time, unlike the short-run demand for electricity, the FCC's demand for licenses is not inelastic, and we account for this in our subsequent analysis of the reverse auction.

Equation 2 implies that certain types of DMAs are more vulnerable to a supply reduction strategy and that certain types of broadcast TV licenses are more suitable for this type of behavior. First, ideal markets from a supply reduction perspective are DMAs in which the FCC will likely need to acquire a positive number of broadcast licenses and where, at the expected demand levels, closing prices for selling stations are likely to change significantly should a lower value station be removed from the auction. This maximizes the impact of withholding a license from the auction on the closing price (the left-hand side of equation 2). Second, suitable groups of licenses consist of some stations with higher broadcast volume to sell into the auction and some with lower broadcast

[14] This mechanism is also similar to the upper bound of the "bidder exclusion effect" considered by Coey, Larsen and Sweeney (2015) in the case of a non-random merger of auction participants.

volume to withhold. We return to these implications of the model below when discussing the data and our results.

3 Data and descriptive evidence

We begin by describing the various sources of data used in the analysis and then turn to providing descriptive evidence in support of the model from Section 2.2.

3.1 Data sources

We use several sources of data to construct firm valuations, determine how non-selling TV stations would be repacked, and summarize the likely spectrum demand in a given market in the forward auction. First, we rely on the MEDIA Access Pro Database (2003 - 2013) from BIA Kelsey (henceforth BIA) and the Television Financial Report (1995 - 2012) from the National Association of Broadcasters (NAB) to estimate a TV station's cash flows and from them infer its reservation value going into the auction.

BIA contains the universe of broadcast TV stations. It provides station, owner, and market characteristics, as well as TV stations' transaction histories covering the eight most recent changes in ownership. The BIA's revenue measure covers broadcast-related revenue in the form of local, regional, and national advertising revenue, commissions, and network compensation. We refer to BIA's revenue measure as advertising revenue in what follows. For commercial stations, advertising revenue is missing for 30.9% of station-year observations, which we impute as detailed in Appendix A.1.3. For non-commercial stations, advertising revenue is missing for 99.7% of station-year observations and we do not impute it.

The BIA data excludes non-broadcast revenue, most notably, retransmission fees. These are fees TV stations charge pay-TV providers to use their content, which the trade press mentions as a small but growing source of revenue for many TV stations.[15] Outside estimates suggest that advertising revenue accounts for a declining share of a typical station's revenue, estimated at 69% in 2016, with the remaining revenue coming from retransmission fees (24%) and online revenues (7%).[16] Consequently, the variation in advertising revenue across stations is a major, but not the sole, driver of the variation in cash flows and thus willingness-to-sell in the reverse auction.

To get at non-broadcast revenue and ultimately profitability, we rely on NAB as a second source of data. For commercial full-power stations, NAB collects financial information. Revenue is broken down into detailed source categories from which we are able to construct advertising revenue and non-broadcast revenue. NAB further covers expenses related to programming, advertising, and other sources, and profitability as measured by cash flows. However, for confidentiality reasons, NAB reports only the distributions of these measures (the 25^{th}, 50^{th}, and 75^{th} percentiles, as well

[15] See, e.g., "SNL Kagan raises retrans fee forecast to $9.8B by 2020; Mediacom's CEO complains to FCC", FierceCable, July 7, 2015.

[16] "Retrans Revenue Share Expands In Latest U.S. TV Station Industry Forecast", Justin Nielson, S&P Global Market Intelligence, Jul 14, 2016.

as the mean) at various levels of aggregation, resulting in "tables" such as "ABC, CBS and NBC affiliates in markets ranked 51-60 in 2012" or "CBS affiliates in markets ranked 1-50 in 2012." Appendix Table 15 lists the set of 66 tables for 2012; other years are very similar. In Section 4 we describe a method to combine the station-level data on advertising revenue from BIA with the aggregated data from NAB to estimate a TV station's cash flows.

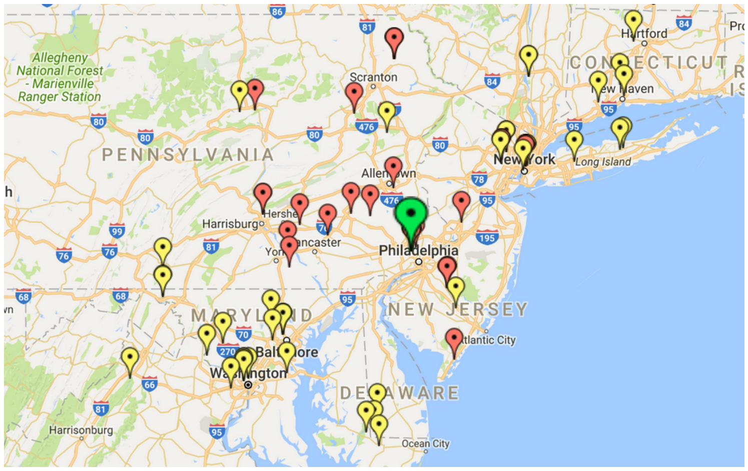
To simulate the repacking process required to construct a contiguous spectrum block out of acquired TV broadcast spectrum, we use three inputs available from the FCC: a TV station interference file, a TV station domain file, and a repacking feasibility checker that takes these two files as inputs.[17] The first file lists, for every TV station and every channel, sets of other TV stations that cannot be located on the same channel, or alternatively cannot be located on adjacent channels, due to interference constraints given the stations' facility locations. Looking only at the UHF channels that would exist if the 126 MHz clearing target had been met (channels 14-30), this file lists 2.5 million pairwise restrictions between broadcast TV stations. As an example, Figure 1 shows the set of the 102 TV stations that have interference constraints with WCAU, the Philadelphia affiliate of NBC. Of those, 37 have adjacent-channel constraints, meaning that they cannot even be located one channel above or below WCAU in the repacked region of spectrum, while the rest have same-channel constraints. Interference is influenced by several factors, including geography, broadcast tower height, and the transmitter's power output. The second file, the domain file, provides a list of channels that a given station may be assigned to in repacking. For most UHF stations, the set of valid channels is the set of all UHF channels, although some have fewer due to international broadcasters or military broadcasting. Relying on these two inputs, the so-called SATFC feasibility checker ascertains whether or not a set of stations can be feasibly repacked into a set of channels given interference constraints and constraints on station channel locations. SATFC is run as part of the reverse auction and uses optimized approaches to NP-complete problems to limit the space of problems to be considered.

Last, the simplified reverse auction model above pointed to DMA-level spectrum demand as a determinant of the likely success of strategic supply reduction. To construct a simple demand estimate, we rely on output of a large-scale simulation exercise conducted by the FCC to determine the likely number of UHF stations it has to acquire in each DMA to meet a nationwide clearing target of 120 MHz.[18] The FCC performed 100 simulations that differ in the identity of the TV stations that do not relinquish their licenses and require repacking after the auction. We restrict attention to the 27 repacking simulations that assume full participation by UHF auction-eligible licenses. For our initial descriptive analysis, we label a DMA as a positive demand DMA if at the median across these simulations the FCC expected to acquire at least one license. Figure 2 shows that in many DMAs no licenses need to be acquired in expectation to meet this clearing

[17] All three files are available at http://data.fcc.gov/download/incentive-auctions/Constraint_Files/.

[18] The FCC also conducted a similar simulation exercise to derive the likely number of stations to be cleared in each market to satisfy an 84 MHz clearing target. We focus on 120 MHz as it is closer to the Stage 1 clearing target the FCC used in the actual auction, which forms the basis for our simulations. See FCC's Public Notice Appendix, "Analysis of Potential Aggregate Interference," available at https://apps.fcc.gov/edocs_public/attachmatch/DA-14-677A2.pdf, accessed on March 10, 2016.

Figure 1: Interference Constraints for NBC Philadelphia (WCAU)



Notes: Each pin represents the facility location of a TV station. WCAU (NBC Philadelphia) is denoted by a green pin. TV stations denoted by red pins have adjacent-channel interference constraints, while those denoted by yellow pins have same-channel interference constraints. A total of 102 broadcast TV stations have some interference constraint with WCAU.

target; hence, payouts from the reverse auction are expected to be concentrated in a small number of DMAs.

The various data sets use a number of different station identifiers. Below, we identify a station either by its call sign (e.g., WCAU, continuing with the NBC Philadelphia example from above) or by the FCC identifier of the facility from which it broadcasts (e.g., WCAU's broadcast facility ID is 63153).

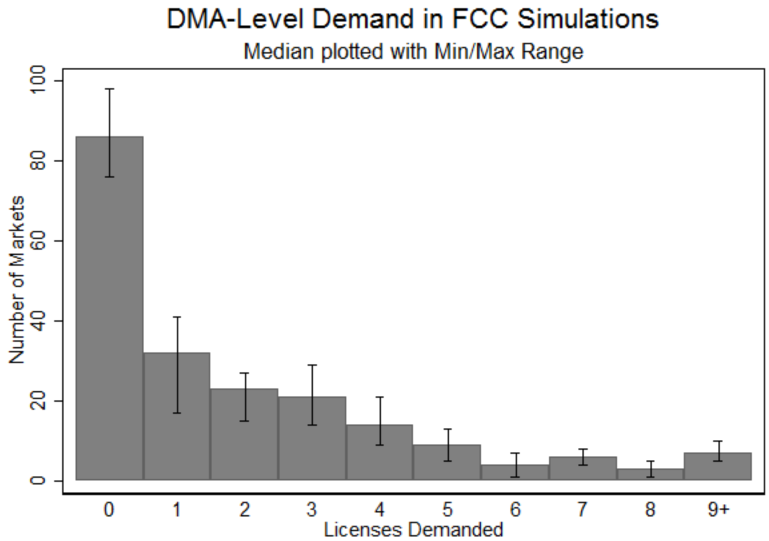
3.2 Descriptive evidence

Our data reveal significant ownership concentration, both within and across DMAs, consistent with the idea of "chains" of broadcasters. We focus on the 1,672 UHF licenses that the FCC denoted as eligible for the reverse auction in November 2014 and used in its own simulation exercises.[19] In 2012, the 1,672 UHF licenses are held by 514 unique owners. Of these 514 owners, 330 hold a single license, 60 hold two licenses, and 37 hold three licenses. The remaining 87 owners hold at least four licenses. Of the 204 DMAs with UHF broadcasters, 79 DMAs have only single-license owners while the remaining 125 DMAs have at least one owner that owns multiple licenses in the DMA.

Ownership concentration has traditionally been a concern of regulators. The FCC Local TV Ownership Rules permit ownership of up to two full-power commercial stations in the same DMA if either the two stations' service areas do not overlap or at least one of the two stations is not ranked among the top four stations in the DMA, based on the most recent audience market share, and at least eight independently owned full-power stations broadcast in the DMA in addition to

[19]The FCC excludes 6 DMAs without UHF stations from its repacking simulations. These DMAs are Bangor, ME, Glendive, MT, Juneau, AK, Lafayette, IN, Mankato, MN, and Presque Isle, ME.

Figure 2: Demand Across DMAs



Notes: This histogram indicates how many DMAs need a given number of licenses to be surrendered in order to meet the overall clearing target to be met in the FCC's simulations. Data are the median, minimum, and maximum of the FCC simulated repacking scenario outcomes that assume 100% participation for the 120 MHz clearing target.

any jointly owned stations.[20] These rules are oriented towards the business of running TV stations that primarily earn revenues through advertising and have a limited effect in preventing a firm from accumulating market power in the reverse auction. Waivers for the rules can be - and have been - granted for failing or financially distressed stations. The rules also do not apply to satellite, public, and low-power stations. However, these types of stations still hold licenses to 6 MHz of spectrum and are eligible for the auction.

Table 1 summarizes ownership patterns, first for all 204 DMAs and then for the 121 DMAs with positive demand under a clearing target of 120 MHz in the FCC's simulations. On average, a positive demand DMA has 9 broadcast TV licenses that are held by 7.15 owners. The number of multi-license owners is 1.36 on average for positive demand DMAs compared to 1.20 for all DMAs. The counts of ownership configurations in the bottom panel of the table reinforce that ownership is more concentrated in positive demand DMAs. In 81 out of 121 or 67% of positive demand DMAs at least one firm owns multiple licenses compared to 125 out of 204 or 61% of all DMAs. Taken together, this suggests that multi-license ownership is a broad concern for the reverse auction.

In addition, news reports have pointed out that at least three private equity firms - LocusPoint Networks, NRJ TV, and OTA Broadcasting - spent almost $345 million acquiring 39 broadcast TV licenses from 2010 to early 2013, mostly from failing or insolvent stations in distress, and mostly

[20]See Title 47 of Code of Federal Regulations, Chapter I.C, Part 73. H, Section 73.3555.

Table 1: Ownership concentration

	All DMAs ($n = 204$)	Positive demand DMAs ($n = 121$)	Private equity active DMAs ($n = 18$)
DMA averages:			
Number of licenses	8.20	9.00	15.94
Number of owners	6.51	7.15	12.22
Number of multi-license owners	1.20	1.36	2.67
Expected number of licenses demanded	2.03	3.42	6.67
Counts of DMAs with j multi-license owners:			
$j = 0$	79	40	3
$j = 1$	53	31	3
$j = 2$	42	30	2
$j = 3$	17	11	3
$j = 4+$	13	9	7

Notes: An observation is a DMA. Table displays average number of licenses, owners, and multi-license owners present in each DMA, together with average of median DMA-level FCC simulated demand at the 120 MHz clearing target. Positive demand DMAs are DMAs where the FCC expects to purchase at least one license (at median) under the 120 MHz clearing target. Private equity active DMAs are DMAs where one of the three private equity firms holds at least one license. Multi-license owners refers to firms owning more than one auction-eligible license within one DMA.

low-power licenses (25 low-power versus 14 full-power licenses).[21,22] Since those press mentions and through the end of our data set in late 2013, an additional 4 license purchases by the three private equity firms were recorded, for a total of 43 license purchases. Of the 43 transactions, 25 are for licenses that cover the same DMA as that of another purchased license and may thus be indicative of attempts to accumulate market power in the reverse auction. Most of the stations are on the peripheries of major DMAs, ranging from Boston, MA, to Washington, DC, on the Eastern Seaboard and from Seattle, WA, to Los Angeles, CA, along the West Coast.

Table 1 illustrates that ownership is especially concentrated in the 18 DMAs in which the three private equity firms have been active (henceforth, private equity active DMAs). The number of multi-license owners is 2.67 on average for private equity active DMAs, and in 15 out of 18, or 83%, of these DMAs at least one firm owns multiple licenses. Moreover, at a 120 MHz clearing target, the FCC anticipated to purchase 6.67 licenses on average in private equity active DMAs compared to 3.42 licenses in positive demand DMAs. In line with the model in Section 2.2, the three private equity firms appear to focus on DMAs with robust demand for spectrum.

Section 2.2 discusses what types of TV stations are best suited for a supply reduction strategy.

[21] See, e.g., http://www.tvnewscheck.com/article/65850/tv-spectrum-speculation-nears-345-millionorhttp://current.org/2013/02/speculators-betting-big-on-fcc-tv-spectrum-auctions/, accessed on November 15, 2015.

[22] According to FCC filings, the Blackstone Group LP owns 99% of LocusPoint Networks. NRJ TV LLC is a media holding company funded through loans from Fortress Investment Group LLC according to a recent U.S. Securities and Exchange Commission filing. Lastly, OTA Broadcasting is a division of MSD Capital, L.P., which was formed to manage the capital of Dell Computer founder Michael Dell.

Table 2 summarizes the characteristics of TV stations transacted from 2003 to 2009 in the first column and those of TV stations transacted from 2010, when the incentive auction was proposed, to 2013 in the remaining columns. The latter are further separated into transactions in the 121 DMAs with positive expected demand under a clearing target of 120 MHz and transactions involving the three private equity firms.

Consistent with the model, the three private equity firms have acquired TV stations with high broadcast volume. They also typically have low valuations, as evidenced by the low prices paid and the fact that very few stations are affiliated with a major network. Even compared to transactions in positive demand DMAs, the TV stations acquired by these firms are particularly high in population reach, interference count, and broadcast volume. Private equity firms also concentrate predominantly on DMAs expected to have positive demand and above average levels of demand: at a 120 MHz clearing target, 98% of their transactions fall into positive expected demand DMAs with average demand of 9 licenses compared to 60% positive demand DMAs with average demand of 3 licenses for all transactions between 2010 and 2013. We caution that most differences between the subsamples are not statistically significant in light of the small sample sizes and large variances of many of the outcomes. In Section 5.1, we return to the model implications and investigate the attributes of licenses that multi-license owners choose to strategically withhold from and bid into the auction.

4 Analysis

We first estimate the reservation value of a TV station going into the auction. Then we simulate the auction and compare the outcome under naive bidding with the outcome when we account for the ownership pattern in the data and allow multi-license owners to engage in strategic supply reduction.

4.1 Reservation values

The reservation value of TV station j in a particular DMA going into the reverse auction held at time t_0 is the greater of its cash flow value $V_{jt_0}^{CF}$ and its stick value $V_{jt_0}^{Stick}$:

$$v_{jt_0} = \max\left\{V_{jt_0}^{CF}, V_{jt_0}^{Stick}\right\}. \tag{3}$$

The industry standard for valuing a broadcast business as a going concern is to assess its cash flow CF_{jt_0} and scale it by a cash flow multiple $Multiple_{jt_0}^{CF}$. Hence, the cash flow value of the TV station is

$$V_{jt_0}^{CF} = Multiple_{jt_0}^{CF} \cdot CF_{jt_0}. \tag{4}$$

This is the price a TV station expects if it sells itself on the private market as a going concern. The stick value $V_{jt_0}^{Stick}$, on the other hand, reflects solely the value of the station's broadcast TV license and tower, not the ongoing business. This is the valuation typically used for unprofitable or non-

Table 2: Broadcast TV license transactions

	2003-2009	2010-2013		
		All	In positive demand DMAs	Involving private equity firms
Number of Licenses Transacted	518	329	199	43
Average Transaction Price ($ million)	47.74	23.00	23.58	8.54
Average Interference Count	68.33	71.74	87.95	92.58
Average Interference-Free Population (million)	1.78	1.92	2.68	3.89
Average Broadcast Volume (thousand)	163.43	177.92	232.97	285.01
Percentage major network affiliation (%)	48.84	52.58	40.70	4.65
Positive Demand DMA (%, at 120 MHz)	58.11	60.49	100	97.67
Average Demand (120 MHz)	2.62	2.94	4.85	8.93

Notes: An observation is a transaction of an auction-eligible station. "Interference Count" is the number of stations with which a given station would interfere if they were located on adjacent channels. "Demand" is the median number of licenses expected to be purchased in the DMA according to the FCC repacking scenarios for the 120 MHz clearing target. "Positive Demand DMAs" refers to transactions that involve a license located in a DMA with a positive median demand level under the 120 MHz clearing target in FCC repacking simulations. For the 507 acquisitions that involve multiple stations, some of which may not be eligible for the auction, we use the average price per license as a transaction price.

commercial broadcast licenses. It is computed from the station's population reach $CoveragePop_{jt_0}$ and the stick multiple $Multiple^{Stick}_{jt_0}$ as

$$V^{Stick}_{jt_0} = Multiple^{Stick}_{jt_0} \cdot 6\, MHz \cdot CoveragePop_{jt_0}. \tag{5}$$

For example, a TV station reaching 100,000 people with a license for a 6 MHz block of spectrum and a stick multiple of \$0.30 per MHz per population (henceforth MHz-pop) is worth \$180,000 based on its fixed assets alone.

While we observe a TV station's covered population, its cash flow is only available at various levels of aggregation in the NAB data. Moreover, we observe neither the cash flow multiple nor the stick multiple. Below we explain how we estimate these objects and infer the station's reservation value v_{jt_0}.

Cash flows. We specify a simple accounting model for cash flows.[23] The cash flow CF_{jt} of TV station j in a particular DMA in year t is

$$CF_{jt} = \alpha\left(X_{jt};\beta\right) AD_{jt} + RT\left(X_{jt};\gamma\right) - F\left(X_{jt};\delta\right) + \epsilon_{jt}, \tag{6}$$

where $\alpha\left(X_{jt};\beta\right) AD_{jt}$ is the contribution of advertising revenue to cash flow, $RT\left(X_{jt};\gamma\right)$ is non-broadcast revenue (including retransmission fees), $F\left(X_{jt};\delta\right)$ is fixed cost, and $\epsilon_{jt} \sim N\left(0,\sigma^2\right)$ is an idiosyncratic, inherently unobservable component of cash flow. Only advertising revenue AD_{jt} and station and market characteristics X_{jt} are directly observable in the BIA data. To estimate the remaining components of cash flow, we specify flexible functional forms of subsets of X_{jt} for $\alpha\left(X_{jt};\beta\right)$, $RT\left(X_{jt};\gamma\right)$, and $F\left(X_{jt};\delta\right)$ and estimate the parameters $\theta = (\beta, \gamma, \delta, \sigma)$ drawing on the aggregated data from NAB.

We proceed using a simulated minimum distance estimator as detailed in Appendix A.2. The parameters $\theta = (\beta, \gamma, \delta, \sigma)$, together with our functional form and distributional assumptions in equation 6, imply a distribution of the cash flow CF_{jt} of TV station j in a particular DMA in year t. We first draw a cash flow error term ϵ_{jt} for each TV station covered by the aggregated data from NAB. Then we match the moments of the predicted cash flow and non-broadcast revenue distributions to the moments reported by NAB for different sets of TV stations and DMAs. In particular, we match the mean, median, 25^{th} and 75^{th} percentiles of cash flow and the mean of non-broadcast revenue for each NAB table in each year, yielding a total of 3,313 moments.

The correlation between the moments of the predicted distributions at our estimates and the moments reported by NAB is 0.98 for cash flow and 0.84 for non-broadcast revenue. The estimates indicate that major network affiliates are most profitable; that non-broadcast revenue has grown significantly in recent years; and that there are economies of scale in fixed cost. Appendix A.2.4 gives details on parameter estimates and fit measures.

[23] In doing so, we follow the Well Fargo analyst report, "Broadcasting M&A 101 Our View of the Broadcast TV M&A Surge," J. Davis Herbert and Eric Fishel, June 26, 2013.

Multiples. To estimate the multiples $Multiple_{jt}^{CF}$ and $Multiple_{jt}^{Stick}$, we begin with the 350 transactions for an individual broadcast TV station in the eleven years from 2003 to 2013 as recorded by BIA.[24] We extract 136 transactions based on cash flows and 201 transactions based on stick values between 2003 and 2013.[25] We infer the cash flow multiple and stick multiple from the transaction price using equations 4 and 5, respectively. Because the transacted stations may be a selected sample, we incorporate industry estimates of the range of the multiples. Using these estimates as priors, we estimate a Bayesian regression model to project multiples on station and market characteristics X_{jt}. This allows us to predict multiples for any TV station, not just those that were recently transacted. Appendix A.3 provides further details. The resulting posteriors, shown in Appendix Figure 11, are a normal distribution for the cash flow multiple and a log-normal distribution for the stick multiple.

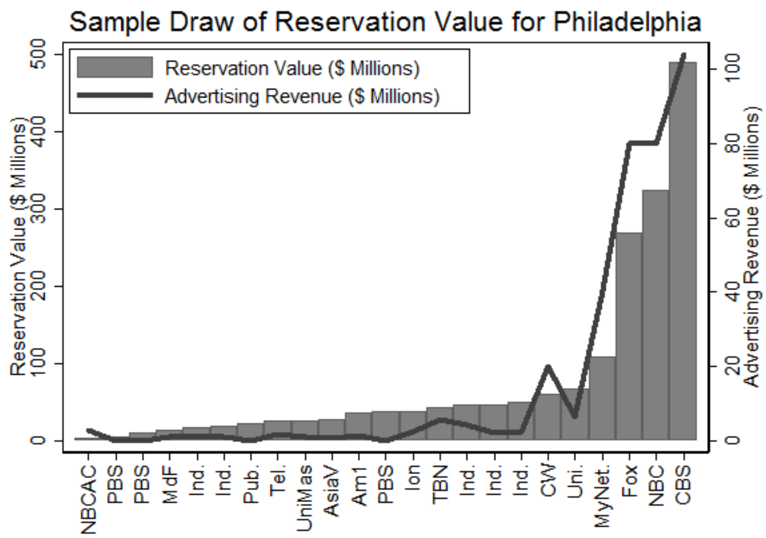
Reservation values. We use our estimates to infer a TV station's reservation value for its broadcast license going into the auction. Not all the 1,672 UHF stations that the FCC includes in its simulation exercise are covered in the aggregated data from NAB that we use to estimate the cash flow model in equation 6. The omissions are 386 low-power UHF stations and 290 non-commercial UHF stations. We therefore extrapolate from our estimates as follows. First, we assume that low-power stations are valued in the same way as full-power stations conditional on station and market characteristics X_{jt}. Second, we assume that non-commercial stations are valued by stick value, consistent with industry practice.

To infer the reservation value of TV station j in a particular DMA going into the reverse auction, we set $t_0 = 2012$ and draw from the estimated distribution of the cash flow error term ϵ_{jt_0} to get $\widehat{CF}_{jt_0}$. We draw from the respective posterior distributions of the multiples to get $\widehat{Multiple}_{jt_0}^{CF}$ and $\widehat{Multiple}_{jt_0}^{Stick}$. A commercial station's reservation value $\widehat{v}_{jt_0}$ is then the higher of the realized draws of its discounted broadcast cash flow value and its stick value as specified in equations 3-5; a non-commercial station's reservation value $\widehat{v}_{jt_0}$ is its stick value. Our estimates imply that the average TV station in our data has a cash flow value of \$42.2 million and a stick value of \$4.5 million. For 31.6% of TV stations, our estimates indicate that the reservation value is given by its stick value rather than its cash flow value.

[24]BIA records 877 transactions with full transaction prices, as opposed to station swaps, stock transfers, donations, etc. We focus on the 350 transactions involving a single license in order to evaluate the trading multiples as a function of station and market characteristics. Of these 350 transactions, 26 involve the three private equity firms.

[25]Because 2012 is the last year of availability for the NAB data, we cannot estimate a TV station's cash flow for 2013. To classify transactions, we proceed as follows: We first define a TV station to be a major network affiliate if it is affiliated with ABC, CBS, Fox, or NBC. We then classify a transaction as based on stick value if it is for a non-major network affiliate with a cash flow of less than \$1 million. Regardless of network affiliation, we also classify a transaction as based on stick value if the TV station has a negative cash flow. Finally, we classify a transaction that would have implied a stick value greater than \$4 per MHz-pop to be based on cash flow and a transaction that would have implied a cash flow multiple greater than 30 to be based on stick value. Together, we drop 13 transactions that do not fit the criteria.

Figure 3: Sample Draw of Valuations for Philadelphia Licenses



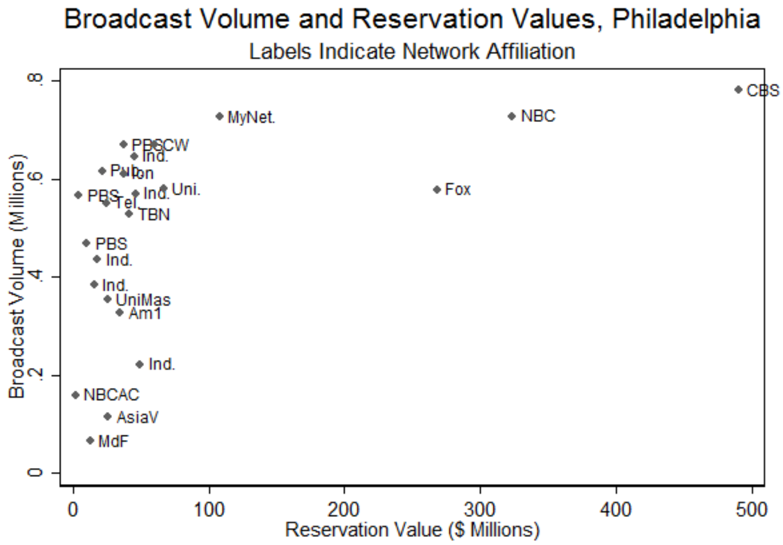
Notes: This chart shows reservation values (left axis), advertising revenues (right axis), and network affiliations (horizontal axis) for all auction-eligible UHF licenses in the Philadelphia DMA, for a single draw from our estimated distributions of valuations and multiples. The Philadelphia ABC affiliate broadcasts from the VHF spectrum and so is not included here.

Example. As an example, Figure 3 shows a sample draw from our estimated reservation values for auction-eligible UHF licenses in the Philadelphia, PA, DMA. The licenses are ordered by their reservation value, and we overlay each license's 2012 advertising revenues from the BIA dataset. In addition, we label each license by its network affiliation on the horizontal axis. It is immediately apparent that our estimated valuations correlate with advertising revenues and network affiliation. In addition, it is clear that reservation values can differ greatly across licenses.

Reservation values are not the same as naive bids in the auction, as pointed out in Section 2.1; since a license is shown a personalized price based on its broadcast volume, two licenses with the same reservation value may have very different clock prices at which they would withdraw from the reverse auction. Figure 4 plots, for the same draw of valuations as above, each license's broadcast volume against its reservation value. While there is some positive correlation, it is far from perfect, and the vertical cluster of licenses on the left indicates that a number of licenses with similar reservation values have broadcast volume levels that are multiples of one another.

As a result of the variation in broadcast volumes, naive bids have a different distribution than reservation values. Figure 5 plots naive bids compared to reservation values. Stations with a relatively low broadcast volume - that are shown a relatively low price in the auction - would withdraw from the auction at relatively higher clock prices. For example, the licenses affiliated with MdF and AsiaV have valuations similar to many other stations, but far lower broadcast volume, meaning that they are shown a relatively lower price than other stations for the same clock price in the auction. Consequently, they would withdraw from the auction at a higher clock price

Figure 4: Correlation of Broadcast Volume and Reservation Values



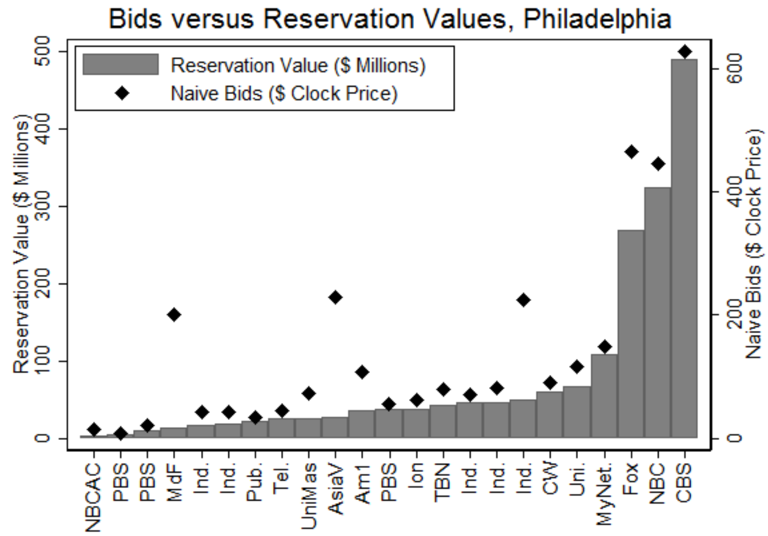
Notes: This scatterplot shows broadcast volume (left axis) against reservation values (horizontal axis) for all auction-eligible UHF licenses in the Philadelphia DMA, for a single draw from our estimated distributions of valuations and multiples.

than a station with a similar valuation but higher broadcast volume, and so their naive bids in terms of the clock price are relatively high.

In other contexts, we would interpret the naive bids in Figure 5 as the elements of a supply curve. Here, however, that would ignore repacking constraints. Since the licenses are not perfectly interchangeable in repacking, the supply of licenses at a given point in the auction depends on what other licenses have already been surrendered. To illustrate, we return to the Philadelphia example in Section 5.2, where we show our simulation auction outcomes for this particular draw of reservation values.

While reservation values alone ignore repacking constraints that together make up supply, they are nevertheless useful in assessing the implications of the basic model in Section 2.2 descriptively, outside of full model simulations. We test whether pre-auction acquisitions are concentrated in vulnerable DMAs where the change in closing clock price is likely large due to supply reduction: we relate the propensity of a purchase by one of the three private equity firms in a probit regression to the increase in reservation values that results from removing from the auction either one or two licenses that would otherwise sell given the median number of licenses the FCC expects to be repurchased in the DMA (the term in parentheses on the left hand side of equation 2). Controlling for population and number of licenses, we find in unreported results that private equity firms were more likely to acquire licenses in DMAs where the distribution of reservation values is relatively steep around expected demand levels and strategic supply reduction is thus likely to be profitable.

Figure 5: Naive Bids and Reservation Values for Philadelphia Licenses



Notes: This chart shows reservation values (left axis), naive bids (right axis), and network affiliations (horizontal axis) for all auction-eligible UHF licenses in the Philadelphia DMA, for a single draw from our estimated distributions of valuations and multiples. ABC Philadelphia broadcasts from the VHF spectrum and is not included here.

4.2 Simulations

To quantify the impact of strategic supply reduction, we solve for all equilibria of a simplified localized version of the reverse auction. Since it is possible, albeit unlikely, that due to interference constraints, the withdrawal of a license in New York, NY, sets the price of a license in Los Angeles, CA, through a series of domino effects, the reverse auction is truly national. Checking the feasibility of repacking a particular station is an NP-complete computational problem that can easily take hours to run. Indeed, according to the FCC's own reports, Round 22 of the first stage of the reverse auction was delayed by one day since the FCC computing engine could not determine the necessary outcomes on time.[26] The computational challenge is further compounded here as we study the impact of strategic supply reduction by enumerating all auction equilibria and integrate over the distribution of estimated cash flows using Monte Carlo simulation.

As a step towards making the analysis computationally feasible, we reduce the size of the nationwide repacking problem by taking repacking constraints into account only at a regional level. Our approach is as follows: for a "focal" DMA $m \in \{1, 2, ..., 204\}$, we define the "region" of DMA m as the set of all DMAs in which at least one station has an interference constraint with at least one station in DMA m. We simulate the auction for a focal DMA m taking all stations in that DMA's region into account, even those stations that do not have any direct interference constraints with licenses in the focal DMA. The object of interest is the payouts in the focal DMA alone. Table

[26]See https://auctiondata.fcc.gov/public/projects/1000/reports/reverse_announcements, accessed on December 9, 2016.

Table 3: Repacking "Regions" of Licenses

	Mean	Min	25th Percentile	Median	75th Percentile	Max
Number of Eligible UHF Licenses:						
By DMA	8.2	1	4	7	11	28
By Repacking Region	83.5	3	54	82.5	112.5	191
Distance Between Eligible UHF Licenses:						
By DMA	34.86	0	1.52	22.44	49.11	414.92
By Repacking Region	184.19	0	107.44	176.61	252.91	779.5

Notes: Statistics are for 204 DMAs with eligible licenses. Distances are in miles. All pairwise distances between stations' broadcast towers in the same DMA or Repacking Region are computed, and statistics are for the full sample of 17,438 pairwise distances within DMAs and 1,751,112 pairwise distances within Repacking Regions.

3 shows that a typical repacking region consists of a far larger set of licenses, and a far more distant set of licenses, than those in a DMA alone. Figure 6 shows the set of TV stations considered to be a part of the Philadelphia region for repacking purposes in our simulations.

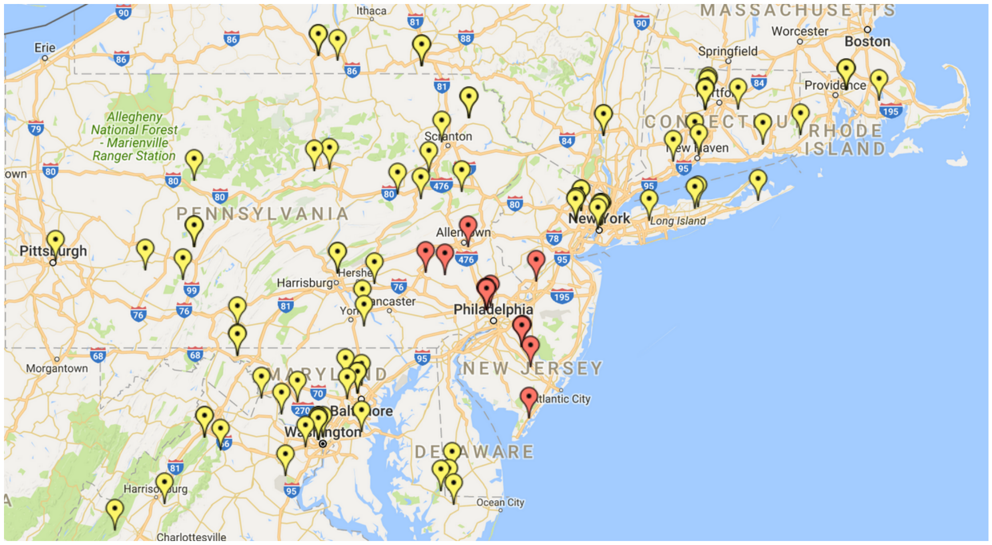
We require a number of additional simplifications. First, to sidestep the forward auction and the multi-stage nature of the overall incentive auction, we fix the clearing target in the reverse auction to be the clearing target used by the FCC in the first round of the actual incentive auction, namely 126 MHz, the clearing target at the time we performed our simulations below. The assumption of a fixed clearing target does not imply that the FCC's demand for a given license is inelastic because there are many sets of licenses that can be repacked to meet the target.

Second, we assume full participation by auction-eligible stations. This is a conservative assumption: concerns have been raised about the possibility of some license holders, such as nonprofit or religious stations, being motivated by considerations beside profitability and choosing not to participate in the reverse auction, even though it would in likelihood be profitable for those stations to surrender their license. In the popular press, several commercial broadcasting chains have shown little interest in the auction, with the CEO of Sinclair Broadcasting Group, which operates 74 stations, stating he "hasn't heard of any broadcaster who has said they have anything for sale."[27] We consider the effect of partial participation specifically by non-commercial station types in Section 5.5 and find that total payouts can easily double, even in the absence of strategic bidding, if participation is low among such stations.

Third, we focus exclusively on the full surrender of UHF licenses into the auction in line with the FCC's own simulation exercise. We thus set aside VHF licenses and, similarly, do not model a TV station's additional option of moving from a higher to a lower frequency band in order to free up more desirable parts of the spectrum. The price that a VHF station is offered for going off the air and the price that a UHF or a VHF station is offered to move channels are fixed fractions of the price that a UHF station is offered for going off the air. For this reason, the FCC's own auction simulations focus solely on the number of UHF licenses required to meet a given clearing target

[27] "FCC can auction spectrum, but will broadcasters sell?", Joe Flint, The Los Angeles Times, February 17 2012.

Figure 6: The Repacking "Region" for Philadelphia, PA



Notes: Each pin represents the facility location of an auction-eligible UHF broadcast TV station. Stations in the Philadelphia DMA are denoted by red pins. Stations denoted by yellow pins are in other DMAs that have at least one station that has a repacking constraint with a Philadelphia station. A total of 126 broadcast stations are considered to be in the Philadelphia region for the purposes of our analysis.

in its repacking simulations. We also do not consider the option of channel-sharing arrangements. Channel-sharing refers to a situation where two TV stations enter into a private agreement to share a license to 6 MHz of spectrum and split the proceeds from selling the other license into the auction. It is unclear how attractive this option is, in part due to technological constraints.[28] Channel-sharing arrangements are likely to boost participation in the reverse auction, thereby effectively reducing the number of UHF licenses required from regular auction participants to meet a given clearing target.

Fourth, we assume complete information among the owners of TV stations in that they know the broadcast volume φ_{jt_0} and reservation value v_{jt_0} of every TV station. The assumption of complete information greatly simplifies the analysis relative to an asymmetric information formulation. The net effect of this assumption on prices and payouts is ambiguous as it makes it easier for firms to implement supply reduction strategies while also eliminating any possible ex-post regret for multi-license owners. Furthermore, while knowledge of reservation values is a strong assumption, many large broadcasters have engaged consultants to help them estimate valuations heading into the auction. In addition, industry groups of smaller broadcasters have helped their members to similarly estimate valuations in their DMAs. While there may be some residual uncertainty about reservation values, we conjecture that a model with incomplete information has similar but possibly less sharp implications as our current model. In particular, strategic supply reduction with

[28] 6 MHz of spectrum is insufficient for two high-definition video streams. The FCC has piloted a channel-sharing arrangement in Los Angeles, CA, showing that it is technologically feasible for one high-definition video stream and one or more standard-definition video streams to share 6 MHz of spectrum. 6 MHz of spectrum may no longer suffice if a TV station eventually transitions from a high-definition to a ultra-high-definition (4K) video stream.

incomplete information manifests itself by a multi-license owner raising her bid above a station's reservation value instead of outright withdrawing the station from the auction, which could have a smaller impact on closing prices.

Our baseline is the outcome of the reverse auction with naive bidding. Under naive bidding, we simply ignore the ownership pattern in the data and treat TV stations as independently owned. In line with the discussion in Section 2.2, TV license j remains in the auction until the base clock price drops below $\frac{v_j}{\varphi_j}$. To account for uncertainty in our estimates of reservation values, we construct reservation values by repeatedly drawing realizations of the cash flow error term ϵ_j and the multiples $Multiple_j^{CF}$ and $Multiple_j^{Stick}$. Given a particular set of implied reservation values, we proceed as follows to compute the naive bidding outcome (a formal coding of the algorithm is presented in Appendix B):

1. Any participating license in a focal DMA's repacking region whose reservation value is above its starting price is repacked into the available spectrum. If it is not possible to accommodate all of these licenses in the available channel space (UHF channels 14-30 for the 126 MHz clearing target), then the auction is considered to have failed.[29]

2. All remaining licenses are considered "active" in the auction. They are sorted in descending order by their reservation price and are denoted by $j \in \{1, ..., J\}$, where $j = 1$ is the station with the highest reservation value in terms of the base clock price. As the base clock price falls, licenses withdraw one by one. Each time a license j withdraws, we verify that each of the remaining "active" stations in $\{j+1, ..., J\}$ could still feasibly be repacked if it were to withdraw in the next round of the auction. If station $k \in \{j+1, ..., J\}$ can no longer be repacked due to j having withdrawn, it is no longer "active", and instead is "frozen" at the current base clock price. The payout to station k is therefore set by station j, who made it no longer feasibly to repack k.

3. The base clock price drops and the process continues until all licenses are either repacked or frozen.

Unless otherwise noted, we report average auction outcomes based on 100 draws from the distribution of reservation values below. With 204 DMAs, each with its own repacking region, and 100 simulation draws, we determine payouts for 20,400 simulated auctions.

We next account for the ownership pattern in the data. We assume that a multi-license owner engages in strategic supply reduction by withholding one or more of its TV stations from the reverse auction at the outset of the auction. Hence, an owner of n_o TV stations has $2^{n_o} - 1$ possible combinations of licenses to consider bidding into auction, and if there are N_o multi-license owners in the repacking region, there are $\prod_{o=1}^{N_o}(2^{n_o} - 1)$ strategy profiles across firms, assuming again full auction participation by single-license owners. Given computational constraints, this creates an

[29]In practice, it is very rare for the auction to fail. The fail rate for our main results is under 0.7% of simulations, and those cases involve many strategic withdrawals of licenses. It is unclear although perhaps unlikely that massive withdrawals of licenses could constitute equilibria.

infeasibly large strategy space for at least some repacking regions; there are 17 owners with 20 or more TV stations and one owner with 93 TV stations in the data. Hence, we impose a restriction on the strategy space, by limiting strategic bidding to licenses in the focal DMA, rather than all licenses owned by a given firm across the repacking region. This reduces both N_o to only multi-license owners and n_o to only licenses in the focal DMA. For example, a multi-license owner of a given license in the Philadelphia, PA, DMA considers strategic bidding only for that and any other licenses in the Philadelphia, PA, DMA, but not for those held in, say, the Harrisburg, PA, DMA, even though we consider such stations in repacking.

For each of the resulting strategy profiles, we re-run the above algorithm to determine the payouts associated with this strategy profile, assuming that firms bid their valuations for the set of licenses they consider bidding into the auction under the particular profile under consideration. We use these payouts to determine whether a particular strategy profile is an equilibrium outcome of each multi-license owner's strategic choice of licenses to bid into the auction in the focal DMA by verifying the absence of any unilaterally profitable deviations from the strategy. With no or one multi-license owner in a DMA, there is a unique pure-strategy equilibrium set of licenses to bid into the auction. With more than one multi-license owner, there may be multiple equilibria; we enumerate all of them.

To be able to accommodate the large dimensional strategy space under strategic bidding, we make one final simplification in estimating auction outcomes: we do not assert feasibility or compute payouts for stations outside the focal DMA; we instead assume they exit the auction at the same base clock price when they would have exited under naive bidding over the entire repacking region. We assert feasibility only for active licenses in the focal DMA when these licenses exit. Our main results compare naive and strategic outcomes under this simplification. In Section 5.6 we show that in select major markets that we tested, this simplification introduced an error of less than 0.20% in the strategic payouts we computed relative to asserting feasibility and computing payouts for all non-focal DMA stations. It had virtually no effect on naive payouts across all markets. At the same time, computational speed increased by a factor of 15 to 20. To further illustrate how we complete our simulations, Appendix Figure 12 shows the reverse auction process in detail for two alternative strategy profiles of multi-license owners in Philadelphia, PA, for a given draw of simulated valuations. Appendix Figure 13 graphically depicts the auction progress under the first strategy profile by plotting the locations of licenses that withdraw and/or are frozen.

Restricting strategic bidding to the focal DMA, the Pittsburgh, PA, DMA has 4,601 strategy profiles to consider, the largest number of any DMA in our data. The total sum of strategy profiles across the 204 DMAs is 17,316, implying solving a total number of 1,731,600 simulated auctions.[30] We recognize that restricting strategic bidding to the focal DMA is likely to create a lower bound on the effect of strategic bidding by multi-license owners. In Section 5.4 we return to the Philadelphia case study and explicitly allow a particular multi-license owner to strategically bid an additional

[30] In contrast, if we allowed multi-license owners to bid strategically within each repacking region, the number of strategy profiles would be a completely unmanageable $6.89 \cdot 10^{44}$.

license from a neighboring DMA; we demonstrate large effects.

Despite the simplifications, our analysis is near the bound of what can be computed in a reasonable amount of time. The over two million simulations in this paper were completed on a combination of the Wharton High-Performance Computing Cluster and the Amazon EC2 Cloud Computing Platform over a period of just under one month during the summer of 2016, typically utilizing over 500 dedicated cores (without hyperthreading) simultaneously.

5 Results

5.1 Naive versus strategic bidding

We compare the outcome of the reverse auction under naive bidding with the outcome under strategic bidding when we account for the ownership patterns in the data. Table 4 shows the main results: payouts to broadcast TV licenses holders under naive and strategic bidding, broken down into different subsets of DMAs. As there may be multiple equilibria when more than one firm in a DMA controls multiple licenses, we present moments of the resulting payout distributions across equilibria. In a given DMA, we record the minimum, mean, median, and maximum payout level across equilibria for strategic bidding for each simulated set of reservation values. We then average each of these four moments across simulation draws. Table 4 then reports the sum of the payouts across particular groupings of DMAs for each moment. In the following, we focus on comparing payouts under naive bidding to the average equilibrium payout under strategic bidding.[31]

The first thing to remark upon is that strategic bidding generally leads to higher payouts in the reverse auction. This need not be the case: there exist equilibria in DMAs where total payouts are lower due to strategic behavior, although higher for the firm engaged in supply reduction.[32] At the mean payout level across equilibria, strategic bidding is found to increase total payouts from $16.999 billion to $20.740 billion, an increase of 22%. Moving down the table, we see that nearly 99% of payout increases are concentrated in DMAs with two or more multi-license owners. Further, we see that DMAs in which private equity firms are active are an important source of increased payouts. Those 18 DMAs are large, accounting for 70.4% of payouts in the base case; however, they account for 95.7% of the total increase in payouts at the mean due to strategic bidding. In addition, we see that there is some skew to the distribution, with some exceptionally large payout increases at the high end of the distribution for certain strategic equilibria. For example, in the 18 private equity active DMAs, the average *maximum* strategic equilibrium payout across equilibria is 51% greater than the payout under the naive base case. Panel B shows the large spillover effect of strategic bidding: single-license owners, who have no incentive to reduce supply, see payout increases of 19.1% at the mean strategic bidding equilibrium. While multi-licenses owners benefit

[31] In the rare cases where there is no pure strategy equilibrium, we assume firms revert to naive bidding.

[32] A firm can selfishly increase its own profits through strategic bidding, but by withdrawing a license from the auction, it also affects which other licenses are sold in. In some occasions, more expensive licenses are substituted with less expensive ones due to strategic bidding by others.

more in percentage terms, the level of payout increases is actually greater among single-license owners.

Table 4 masks significant heterogeneity in the impact of strategic supply reduction. Even under naive bidding, there are an average of just over 90 DMAs that see payouts of zero across simulations. Under strategic bidding, an average of 23 DMAs, or just 11% of DMAs, show payout increases from strategic bidding.[33]

Our simulations allow us to determine the profitability of strategic supply reduction for the three private equity firms. Table 5 presents the results. As discussed in Section 3.2 these firms have acquired TV stations with high broadcast volume but low valuations as going concerns. Even under naive bidding, the firms stand to profit as their payouts in the reverse auction plus the value of any unsold licenses substantially exceed their total acquisition costs.

The simulations bear out the implication of the model in Section 2.2 that a multi-license owner sells stations with higher broadcast volume into the auction but withholds stations with lower broadcast volume. Table 6 shows the average broadcast volume and reservation value of the licenses owners decide to keep and sell under naive and strategic bidding simulations. Comparing attributes of unsold stations under naive and strategic bidding, we see that owners on average keep stations of lower value and sell stations of higher value under strategic bidding. This is counter-intuitive, until one sees that the stations kept have lower broadcast volume, and so are less valuable in the auction, while those sold have higher broadcast volume, making them particularly attractive to sell into the auction. In general, we see that strategic behavior leads to a higher amount of broadcast volume being acquired to reach the clearing target, increasing the total payouts.

There are two potential efficiency losses from strategic bidding by multi-license owners: first, such behavior changes the set and number of licenses surrendered in the auction; second, such behavior risks reducing the amount of spectrum that is repurposed in the auction.

The set of stations surrendered under strategic bidding differs from that under naive bidding, as implied by Table 6. Therefore, strategic bidding by multi-license owners distorts the set of licenses that are surrendered from a socially optimal set to a different set, allowing perhaps lower-value licenses to remain on-air while higher-value licenses are surrendered. Such efficiency losses are likely significant; our simulations indicate that the average license that remains unsold under naive bidding has a reservation value of less than half of the reservation value of an unsold license in the average strategic equilibrium.

In addition, there is a risk that strategic bidding by multi-license owners could cause a stage of the auction to fail, leading to a reduction of the overall clearing target. As the forward auction is outside of the scope of this paper, we cannot address this prospect numerically, although we mention it as a possibility.

[33] On average, one DMA per simulation will see a decrease in payouts from strategic bidding.

Table 4: Total Payouts ($B) to Broadcast TV License Holders by DMA Type

		Naive Bidding	Strategic Bidding				Payout Increase
Panel A: DMA Payouts ($B) In:	# DMAs	Base	Mean	Min	Median	Max	At Mean
All DMAs	204	16.999	20.740	18.519	20.554	23.301	22.0%
		(0.751)	(0.898)	(0.876)	(1.235)	(1.686)	
DMAs with Multi-License Owners	125	15.611	19.352	17.130	19.166	21.193	24.0%
		(0.718)	(0.875)	(0.864)	(1.220)	(1.666)	
DMAs with Two or more Multi-License Owners	72	14.410	18.108	15.892	17.922	20.663	25.7%
		(0.711)	(0.867)	(0.860)	(1.209)	(1.663)	
Private Equity Active DMAs	18	11.978	15.558	13.382	15.372	18.070	29.9%
		(0.704)	(0.853)	(0.861)	(1.203)	(1.649)	
Panel B: Owner Payouts ($B) Among:							
Single-License Owners (within DMA)	-	12.009	14.309	12.113	14.201	16.556	19.1%
		(0.505)	(0.679)	(1.564)	(0.776)	(1.487)	
Multi-License Owners (within DMA)	-	4.981	6.207	(5.496)	6.222	6.859	24.6%
		(0.363)	(0.367)	(0.584)	(0.427)	(0.440)	

Notes: In the case of naive bidding, payouts are averaged over 100 simulated sets of reservation values. In the case of strategic bidding, the moments of the payout distribution are calculated across all possible equilibria for a given simulated auction and then averaged over 100 auction simulations. Standard deviations of the moments across the 100 simulations are in parentheses. The mean, min, median, and max payouts are computed within DMA, and aggregated to the DMA grouping under consideration in Panel A. In Panel B, payouts are first aggregated among the sets of single-license and multi-licenses owners. The sum of payouts among the two sets of owners does not always equal the value for "All DMAs" in Panel A since statistics are taken among those two groups before averaging and ratios between the two groups differ across markets.

Table 5: Auction Surplus to Private Equity Firms

		Total	Total Profits	
	# Stations	Purchase Price ($M)	Naive ($M)	Strategic ($M)
NRJ	14	235.51	690.79	1, 473.04
			(81.31)	(140.56)
OTA	20	77.05	446.79	1,237.10
			(44.94)	(144.61)
LocusPoint	9	54.75	200.65	400.44
			(24.64)	(62.22)

Notes: Profits are averages over 100 auction simulations, and in the case of strategic bidding, averages over equilibria, summed across all DMAs where the firms hold licenses. Total profits are defined as total proceeds from the auction for stations that sell, plus the reservation values of stations that do not sell, less the purchase prices paid by the firms for the stations.

Table 6: Station Characteristics for Auction Licenses

	Bidding Strategy			
	Naive		Strategic	
License Averages	Unsold	Sold	Unsold	Sold
Broadcast Volume (000s)	156.893	214.051	100.554	343.060
	(2.920)	(8.853)	(4.544)	(18.041)
Reservation Value ($M)	44.959	8.845	32.742	20.072
	(1.254)	(0.827)	(3.750)	(3.929)

Notes: Statistics describe averages of station characteristics for selling and non-selling licenses across all 204 DMAs and 100 auction simulations per DMA, and in the case of strategic bidding, first averaged across equilibria for each auction simulation. Standard errors based on 100 simulation draws are in parentheses.

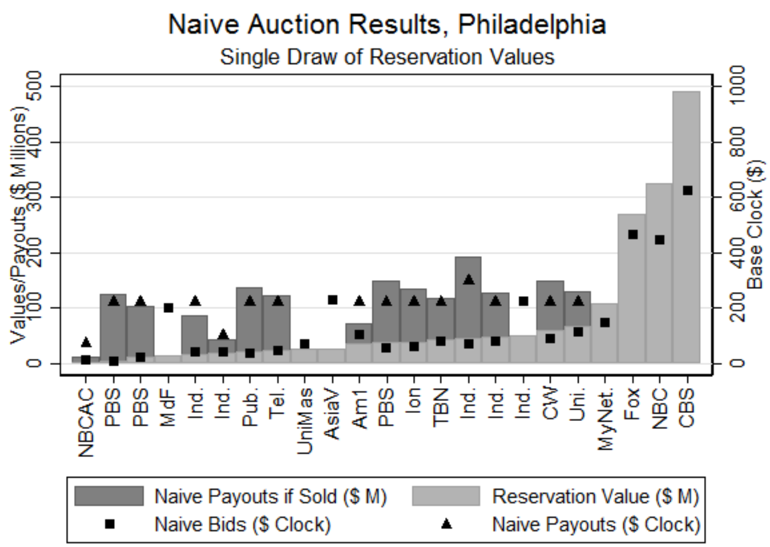
5.2 Case study: Philadelphia, PA

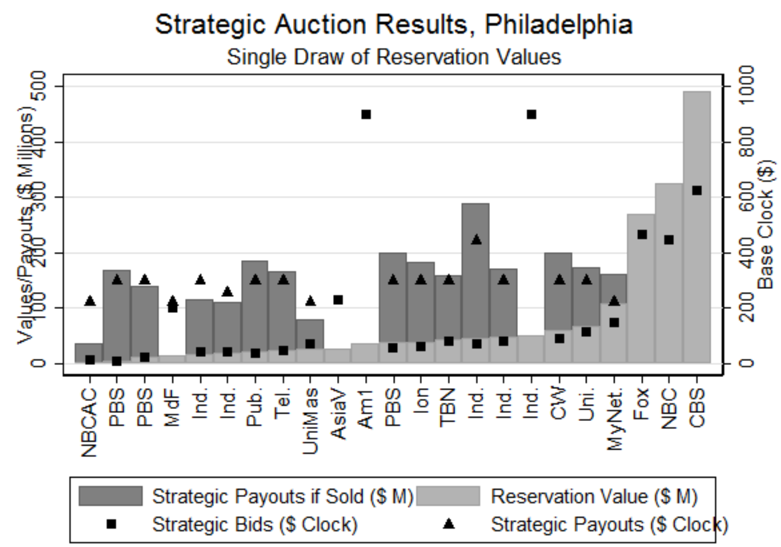
In this section we illustrate the impact of strategic bidding for a particular realization of valuations for stations in the Philadelphia, PA repacking region. Figure 7 shows graphs of outcomes first under naive, and then under strategic bidding. Both charts show all eligible UHF licenses in the focal Philadelphia, PA, DMA ordered by their simulated reservation values in light gray on the left y-axis. We further display on the second y-axis payouts in terms of base clock prices as triangles; recall that the payout in terms of base clock maps to license-specific payouts on the left y-axis through the broadcast volume of each license. Lastly, we display on the second y-axis the firms' bids in terms of base clock prices as squares. These correspond to the stations' transformed reservation prices and indicate the base clock price at which the station would drop out of the auction, if it is not frozen at a higher base clock price. The first image shows the outcome under naive bidding. In the second, we present a strategic equilibrium of this simulation where two multi-license owners each are able to increase their own auction surplus by withdrawing one of their licenses from the auction (these licenses are identified by strategic bids of $900, which is the starting base clock price of the auction). Note that the withdrawal of two licenses increases payouts for several other licenses, implying a positive spillover to those licensees, but the two firms find it individually rational to withdraw licenses solely based on their own profit motives. Total payouts in this DMA go from nearly $1.7 billion for 15 licenses under naive bidding to over $2.5 billion for 16 licenses in the strategic equilibrium presented here. This example thus clearly indicates the inefficiencies associated with strategic bidding: not only is it possible that the mix of stations that sells in the auction is distorted (e.g., UniMas does not sell under naive bidding but does under strategic bidding, while MyNetwork TV sells under strategic bidding but not under naive), but strategic bidding may also result in the government needing to purchase a larger number of licenses to reach its predetermined clearing target given the interference patterns between the stations that are now not selling in the auction.

Appendix Figure 12 shows the precise details of these two simulations, with the naive bidding simulation in the left column and strategic on the right. The figure shows the order in which licenses withdraw from the auction and the base clock price at which they withdraw, labeling licenses by their FCC Facility ID number, and including their network affiliation in parentheses. Importantly, the figure emphasizes that we repack a large region around the DMA, by highlighting the few licenses in the Philadelphia, PA, DMA in bold. The left column of the figure shows how major network affiliates in large markets withdraw from the auction immediately, as starting base clock prices are too low. For example, License #9610 is CBS New York, and it withdraws immediately from the auction. Reading down the column, we see how licenses withdraw and how all remaining licenses are then checked for feasibility in repacking. If a license can no longer be feasibly repacked due to a withdrawal, its payout is frozen based on the current clock price. We only list freezes for licenses in the focal Philadelphia, PA, DMA.

The right column of the figure shows how the strategic withdrawal of two licenses changes the prices at which other licenses become frozen in the auction. For example, license #39884

Figure 7: Sample Outcomes under Naive and Strategic Bidding in Philadelphia





Notes: Data are for a single simulation draw of reservation values. Under strategic bidding, two stations withdraw from the auction (effectively having naive bids above the opening price). This raises payouts for many other stations in this particular simulation. The strategic outcome shown here is an equilibrium for this simulation, as the two private equity firms that withdraw licenses are able to increase their profits from this behavior. From the left, the stations owned by NRJ are numbers 11 and 16 (Am1 and Ind affiliations), while the ones owned by LocusPoint are in positions 1 and 17 (NBCAC and Ind affiliations). The simulation takes into account the repacking of all 126 licenses in the Philadelphia repacking region.

becomes frozen by the withdrawal of license #73333 at a clock price of $298.15 in the naive bidding simulation, but in the strategic simulation, it is frozen earlier by the withdrawal of license #63153 at a clock price of $444.89, increasing its payout by 49% even though its owner is not the firm withdrawing licenses. The two multi-license owners who own pairs (#74464, #55305) and (#61111, #72278), find withdrawing licenses a profitable strategy individually.[34]

5.3 Partial remedy

We have so far shown that strategic supply reduction may lead to increased payouts and efficiency losses in the reverse auction. We next analyze a change to the auction rules and show how it limits the potential for rent-seeking. The model in Section 2.2 shows that strategically reducing supply is more likely to be profitable if the increase in the closing base clock price from withholding a license can be leveraged by selling a license with high broadcast volume into the auction. The rule change we analyze aims to weaken this mechanism by limiting the strategy space of multi-license owners. In particular, we stipulate that a multi-license owner must first withdraw her highest broadcast volume license. Once that has been withdrawn from the reverse auction, the owner may withdraw her second highest broadcast volume license, and so on.

Table 7 shows how the rule change affects our main results. The increase in payouts from strategic bidding are 80% less than in Table 4 at the mean. Interestingly, under this alternative policy, the outcome under strategic bidding presented in Figure 7 for the Philadelphia, PA, DMA would no longer involve feasible strategies since there, both firms withhold their lower broadcast volume stations. This would thus cease to be an equilibrium outcome.

Efficiency requires that, for otherwise identical licenses, the licenses with the lowest reservation values are sold into the auction. In the spirit of the literature on regulation where effort is not verifiable (Laffont and Tirole, 1986), the rule change leverages the fact that broadcast volume, unlike cash flows, is observed and contractible. Our estimates imply that broadcast volume is positively correlated with reservation value: averaged across simulation runs the correlation is 0.47 overall and 0.44 within DMA.[35] The rule change therefore mitigates efficiency losses by requiring that licenses with higher broadcast volumes, and likely higher reservation values, are withdrawn first from the reverse auction.

The rule change has two potential shortcomings, aside from legal considerations. First, a multi-license owner may be able to circumvent the rule change by selectively entering her licenses into the reverse auction in the first place. However, the rules of the auction may be further rewritten to compel a multi-license owner to either participate with all her licenses in the auction or not at all. Second, and perhaps more importantly, forcing lower broadcast volume licenses to sell before

[34] NRJ who withdraws #74464 foregoes a surplus on that license of $37.5 million = ($221.79-$106.71)*326127.3, which is the naive clock payout less reserve value measured in terms of base clock price times broadcast volume, in exchange for increasing the payout in terms of clock price for license #55305 from $221.79 to $298.15, which when multiplied by a broadcast volume of 570169.3 is $43.5 million. LocusPoint that withdraws #72278 loses nothing on that license as it does not sell under naive bidding, but its withdrawal increases the payout to license #61111 by $23.8 million, by raising the freezing clock price from $72.66 to $221.79, given a broadcast volume of 159417.7.

[35] Within DMA correlations are averaged over 184 DMAs that have three or more stations.

Table 7: Total Payments ($B) by DMA Type under Rule Change

Payouts ($B) under:		Naive Bidding	Strategic Bidding				Payout Increase
	# DMAs	Base	Mean	Min	Median	Max	At Mean
All DMAs	204	16.999	17.735	17.097	17.826	18.343	4.3%
		(0.751)	(0.753)	(0.729)	(0.840)	(0.834)	
Multi-License Owners	125	15.611	16.347	15.709	16.437	16.955	4.7%
		(0.718)	(0.715)	(0.694)	(0.806)	(0.798)	
Two or more Multi-License Owners	72	14.410	15.129	14.495	15.220	15.734	5.0%
		(0.711)	(0.711)	(0.690)	(0.797)	(0.799)	
Private Equity Active	18	11.978	12.656	12.034	12.747	13.249	5.7%
		(0.704)	(0.698)	(0.688)	(0.779)	(0.790)	

Notes: Data are averages over 100 auction simulations. Standard deviations across 100 simulations are in parentheses. Auction mechanism assumes that multi-license holders withdraw license with highest broadcast volume first. See Notes to Table 4.

higher broadcast volume licenses may complicate the repacking process to the extent that licenses with higher broadcast volume and potentially also higher interference count may no longer sell and have to be repacked.

5.4 Multi-market strategies

Strategic bidding may extend beyond market borders if multi-license owners withhold a license in a DMA from the reverse auction to drive up the closing base clock price in a neighboring DMA where they also own a license. Here, we illustrate how such strategies may work continuing with the Philadelphia, PA, case study. As mentioned above, it is not computationally feasible to consider all multi-market strategies in a repacking region, given the prevalence of multi-license ownership and the need to simulate over uncertainty in reservation values.

In late 2012 NRJ purchased WGCB-TV in the Harrisburg, PA, DMA for $9 million. While NRJ owns no other TV stations in the Harrisburg, PA, DMA the firm had previously purchased WTVE and WPHY in the Philadelphia, PA, DMA in late 2011 and early 2012 for $30.4M and $3.5M respectively. WGCB-TV has a very high interference count and may interfere with 161 stations in the repacking process. A closer look shows that WGCB-TV is not actually located in Harrisburg, PA, but in Red Lion, PA, towards both the Philadelphia, PA, and Baltimore, MD, DMAs. Figure 8 shows how the broadcast contours of WGCB-TV and WTVE overlap. Hence, if NRJ withdraws WGCB-TV from the reverse auction, this may sufficiently complicate the repacking process to increase demand in the Philadelphia, PA, DMA, and potentially other DMAs.

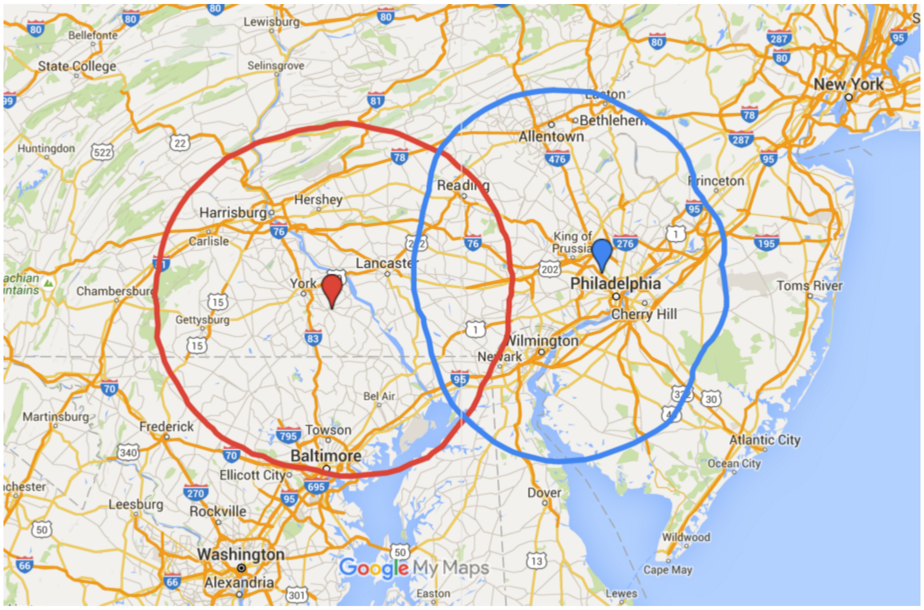
Table 8 shows the effect on payouts in the Philadelphia, PA, focal DMA of allowing NRJ to bid its license to WGCB-TV strategically in concert with its licenses in the Philadelphia, PA, DMA. We continue to assume that all remaining multi-license owners in the Philadelphia, PA, DMA, to the extent that they own licenses outside that focal market, consider strategic bidding for their Philadelphia stations only. From a practical perspective, this relocates the license of WGCB-TV from the Harrisburg DMA to the Philadelphia DMA for ownership purposes without actually relocating the broadcast tower. This change alone increases the number of strategy profiles to consider from 729 to 1701 for each simulation draw.

The first row in Table 8 shows Philadelphia's results from our main results in Table 4. The first and second rows show that the rule change proposed in Section 5.3 is very effective in this DMA. The third row shows that total payouts can increase dramatically in this DMA if NRJ bids its Harrisburg license strategically. The fourth row shows that the partial remedy is no longer particularly effective in this situation, suggesting that our above estimate is likely an upper bound of the true degree to which the remedy would restrain the extent to which strategic bidding can influence payouts.

Note that all payouts in the table exclude any payout to WGCB-TV, so they are directly comparable across scenarios. In particular, one can see that having an additional strategic lever is valuable in the tail end of equilibrium payouts in this case study.

More generally, cross-market ownership can be seen as positive for the auction, as selling licenses

Figure 8: Multi-Market Strategy in the Mid-Atlantic



Notes: Map plots reception contours from FCC TV Query database for WGCB-TV (Harrisburg) in red and WTVE (Philadelphia) in blue. Contour plots reflect reception of DTV signals from the broadcast towers. Image via Google Maps.

should be complementary across markets if it allows a larger clearing target to be attained. However, in this context, it has the potential to be negative if withdrawing WGCB-TV from the auction sufficiently complicates repacking in Philadelphia: NRJ may find it worthwhile to withdraw WGCB-TV from the auction if either the proceeds from selling WGCB-TV are low, or if NRJ's increase in profits from its Philadelphia licenses is large.

5.5 Partial participation

So far, we have conservatively assumed full participation on behalf of all eligible UHF licensees. We now consider what payouts may be under reduced participation. In particular, the results in Table 9 show total payouts when we assume that across simulation draws, both a) none of the religious stations participate, and b) a random subset of 50% of non-commercial stations does not participate, for a total of 253 non-participating licenses in each simulation draw. The results highlight how important full participation is to the auction's success. First, limited participation makes the failure of the auction significantly more likely, as all of the licenses in the non-participating group, and any other stations that were identified as participating but that have reservation values in terms of the base clock price above the auction's starting point, need to be repacked for the auction to even be able to start. This means that in 4.2% of all 20,400 naive bidding simulations under reduced participation, the auction immediately concluded as a failure, which never occurred under full participation. It is immediately clear that low participation - before any strategic withdrawal of licenses - can have dramatic effects on payouts, nearly doubling them. The first row of

Table 8: Case Study: Philadelphia PA DMA Multi-Market Strategy

Payouts ($B) under:	Naive Bidding	Strategic Bidding				Payout Increase
	Base	Mean	Min	Median	Max	At Mean
Philadelphia, Base Case	2.172	2.481	2.320	2.499	2.614	14.2%
	(0.241)	(0.466)	(0.450)	(0.548)	(0.637)	
Philadelphia, Base Case, Remedy	2.172	2.215	2.189	2.223	2.231	2.0%
	(0.241)	(0.294)	(0.244)	(0.328)	(0.333)	
Philadelphia, NRJ Strategic with WGCB-TV	2.172	4.065	2.141	3.995	6.190	87.2%
	(0.241)	(0.201)	(0.322)	(0.258)	(0.525)	
Philadelphia, NRJ Strategic with WGCB-TV,	2.172	3.803	2.172	3.824	5.614	75.1%
Remedy	(0.241)	(0.291	(0.241)	(0.318)	(0.426)	

Notes: See notes to Table 4. We depict total payouts under NRJ bidding all of its licenses in the Philadelphia repacking region strategically in the third and fourth rows. Payouts in rows 3 and 4 do not include any payments to WGCB-TV.

Table 9: Naive Outcomes under Reduced Participation

Payouts ($B) under:	# DMAs	Naive Bidding		Payout Increase from
		Full Participation	Limited	Limited Participation
All DMAs, No-Fail Simulations	204	16.999	33.869	99.2%
		(0.751)	(2.005)	
No-Fail Positive Payout DMAs	45	5.545	10.341	86.5%
		(0.265)	(0.867)	

Notes: Data are averages over 100 auction simulations. Standard deviations across 100 simulations are in parentheses. Limited participation means that no religious stations participate (108 licenses) and that a random subset of 50% non-commercial stations do not participate (145 additional licenses). The "All DMAs" row is conditional on auction non-failure. "No-Fail Positive Payout DMAs" is a set of markets that always see positive payouts, yet never see the auction fail across 100 simulations.

Table 9 shows that, conditional on the auction not failing, payouts would effectively double due to non-participation by religious and some non-commercial licensees. To avoid comparing subsets of simulation draws from different markets, the second row limits the sample to DMAs that always see strictly positive payouts and yet never see auction failure under lowered participation; the effect is nearly as dramatic, with an 86.5% increase in payouts.

The fact that the mechanism is sensitive to participation leads us to a second recommendation. The likely reason many small broadcasters would choose to remain on-air relates to "must-carry" provisions in FCC regulations. While the regulations are fairly complex, they stipulate that a large cable operator must carry any and all local broadcast stations, unless such a station has opted-out and requested retransmission fees.[36] Therefore, continuing to broadcast guarantees that many small licenses will be carried on cable, which greatly broadens their reach or potential advertising audience. One simple measure to increase participation, therefore, would be to allow broadcasters to relinquish their spectrum licenses but retain their must-carry status, so that they can continue to operate as businesses and reach viewers through cable systems.

5.6 Robustness of Repacking Approach

Here, we consider the effect of how our simulations limit repacking on outcomes. Our main results for both naive and strategic bidding rely on simulations that do not assert the feasibility of repacking of licenses outside the focal DMA, but instead assume that these licenses withdraw or are frozen at the same time as when we assert feasibility for all stations in the entire region under naive bidding. A more complete but computationally intensive analysis of strategic bidding would assert feasibility for all regional licenses to determine at which points licenses withdraw or are frozen in the auction under each strategy profile, in effect treating all licenses in the region as if they were in the focal DMA. We denote the full analysis of bidding by all stations in the repacking region

[36] Any cable operator offering more than 12 channels must set aside one-third of their channel capacity for local commercial broadcasters. Any cable operator offering more than 36 channels must carry all non-commercial and educational broadcasters.

Table 10: Naive Outcomes under Robust Repacking

Payouts ($B) under:	Naive Bidding
All DMAs	16.9994
	(0.7513)
All DMAs, Robust Repacking	16.9655 (0.7330)

Notes: Data are averages over 100 auction simulations. Standard deviations across 100 simulations are in parentheses. Robust repacking implies that payouts and feasibility were computed and asserted for all licenses in the region, as opposed to only the focal DMA.

as "robust repacking" in the following. To assess the implication of our simplification, we perform two exercises. First, we compare our naive repacking results to naive robust repacking results for all DMA markets; second, we compare our strategic repacking results to strategic robust repacking results for two important DMAs.

We first compare naive bidding outcomes when we robustly assert feasibility for all licenses in the region to the above outcomes when assuming that licenses outside the focal DMA are frozen or repacked at the same point in the auction as occurs under robust repacking, without explicitly asserting feasibility. The latter simplified repacking procedure greatly decreases the computational burden by more than an order of magnitude. Table 10 shows the results for all DMAs. The assumption has a very limited effect on payouts under naive bidding, with robust repacking reducing total payouts by just under 0.2%. In addition, the correlation between payouts in all 20,400 simulations is 0.9997.

We then consider how strategic bidding outcomes would change if we continued to account for feasibility of all licenses in the region, instead of only those licenses in the focal DMA. To assess these issues, we simulated the robust regional repacking for all strategy profiles for the New York, NY, (729 strategy profiles for each simulation draw) and Washington, DC, (189 strategy profiles for each simulation draw) DMAs, as doing so for all DMAs would not be computationally feasible. Note that while we thus treat all licenses in the region as though they were part of the focal DMA for repacking purposes, we continue to assume that strategic bidding occurs only between licenses within the focal DMA, but not between all licenses a firm owns across the full repacking region. Table 11 shows the results of this exercise, and affirms that the impact of the repacking simplification on strategic outcomes is very small. Our intuition is that robust repacking is more flexible and so leads to lower payouts, although the results in these two markets suggest that the impact is negligible.

6 Conclusions

In this paper we explore ownership concentration as a means to seek rents in the context of the U.S. government's acquisition of broadcast TV licenses in the ongoing incentive auction. Ownership concentration is an important policy concern as the FCC has worried about encouraging a healthy

Table 11: Strategic Outcomes under Robust Repacking

Payouts ($B) under:	Total	Naive Bidding	Strategic Bidding				Payout Increase
	Simulations	Base	Mean	Min	Median	Max	At Mean
New York, NY	72,900	2.363	3.086	2.363	3.096	3.893	30.6%
		(0.216)	(0.295)	(0.216)	(0.330)	(1.013)	
New York, NY	72,900	2.363	3.086	2.363	3.095	3.893	30.6%
Robust Repacking		(0.216)	(0.296)	(0.216)	(0.330)	(1.013)	
Washington, DC	18,900	0.290	0.327	0.317	0.328	0.338	12.9%
		(0.071)	(0.065)	(0.063	(0.067)	(0.085)	
Washington, DC	18,900	0.290	0.326	0.316	0.327	0.337	12.9%
Robust Repacking		(0.071)	(0.065)	(0.063)	(0.066)	(0.0084)	

Notes: Moments of the payout distribution are calculated across all possible equilibria for a given simulated auction and then averaged over 100 auction simulations. Standard deviations of the moments across the 100 simulations are in parentheses. Robust repacking implies that payouts and feasibility were computed and asserted for all licenses in the region, as opposed to only the focal DMA. Payout increase percentages are computed with full precision and so may not correspond to values computed from this table.

supply of licenses in the reverse auction and has viewed outside investors as more likely to part with their licenses than potentially "sentimental" owners. Our prospective analysis shows that this is likely to give rise to strategic supply reduction and raise the cost of acquiring spectrum.

In particular, we argue that firms may engage in rent-seeking by attempting to reduce supply of broadcast TV licenses in the reverse auction. We conduct a large-scale valuation exercise for all UHF auction-eligible broadcast licenses in order to highlight the potential for strategic supply reduction and quantify the resulting increases in payouts and efficiency losses. The effect of ownership concentration can be substantial, and this paper is the first attempt to quantify this effect.

For the auction's initial clearing target of 126MHz, on which we base the simulations in this paper, the first stage of the reverse auction resulted in a spectrum acquisition cost of $86.4B, far exceeding the revenue the FCC was able to realize in the forward auction, a total of only $23.1B. Our base specification shows instead payouts of only roughly $17B in the reverse auction, which would have been low enough to end the incentive auction after the first stage.

While the goal of our paper is not to attempt to predict the exact reverse auction outcome, our broad findings indicate that it is likely that both participation below 100% and strategic bidding may have contributed to the failure to clear the opening target. Our results in Section 5.5 suggest that participation of less than 50% of eligible noncommercial stations nearly doubles spectrum acquisition costs, even in the absence of any strategic bidding. Strategic supply reduction, even when constrained to licenses in the same DMA market, increases broadcaster payouts by 22%, on average, as we show in Section 5.1. In a case study of cross-market strategic supply reduction, as would have likely taken place in the auction itself, payouts due to strategic bidding increased by a much more significant 87.2%. While computational constraints do not allow us to investigate whether the particular Philadelphia case study is representative of the effect of cross-market strategic supply reduction in other DMAs, the results in Section 5.4 suggest that our baseline strategic supply reduction effects are likely a lower bound on the true extent of rent seeking that could arise in the auction due to multi-license ownership.

The execution of the incentive auction, the most novel auction designed since the inception of spectrum auctions, is an incredibly difficult task that, based on current indications, has been very successfully tackled. We do not take a stand on whether any specific action would have altered the bidding results in the reverse auction. For example, it is impossible for us to assess whether full participation could ever have been achieved. We hope nevertheless that our work proves useful in designing future auctions geared at repurposing spectrum toward more efficient use.

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A Appendix: Data

A.1 Sample construction and primary variables

In this appendix, we describe how we construct the sample of DMAs and TV stations used and discuss several details of the data sources we rely on. Our objective is to infer a TV station's reservation value going into the auction from its cash flow or population coverage scaled the appropriate multiple. While the auction is scheduled for March 2016, we infer a TV station's reservation value as of 2012 as the latest year of availability for both the BIA and NAB data. Our analysis is further made difficult by the fact that different data sources cover different TV stations.

A.1.1 DMAs

The U.S. is divided into 210 DMAs. DMAs are ranked annually according to market size as measured by the total number of homes with at least one television (henceforth, TV households, measured in thousand). Table 12 lists the top ten DMAs in 2012 along with some characteristics from the BIA data.

Table 12: Top Ten DMAs (2012)

Rank	DMA	TV Households	Station Count	Income ($)
1	New York, NY	7,388	19	49,518
2	Los Angeles, CA	5,570	24	36,972
3	Chicago, IL	3,493	18	40,500
4	Philadelphia, PA	2,993	19	42,034
5	Dallas-Ft. Worth, TX	2,571	17	37,215
6	San Francisco-Oakland-San Jose, CA	2,507	18	53,448
7	Boston, MA	2,380	16	48,294
8	Washington, DC	2,360	11	49,495
9	Atlanta, GA	2,293	13	33,726
10	Houston, TX	2,185	14	40,704

Notes: Includes all auction-eligible commercial full-power and low-power (class-A) TV stations. Income is average per capita disposable personal income. Source: BIA.

A.1.2 TV stations

Table 13 shows counts of auction-eligible TV stations as of 2012, broken down by power output, type of use, and type of service. There are a total of 2,166 auction-eligible TV stations. We focus on the 1,672 UHF stations that the FCC includes in its repacking simulations.

A.1.3 BIA data

After restricting to full-power (primary and satellite) and low-power (class-A) stations, the BIA data provides us with 24,341 station-year observations from 2003 to 2013. Commercial stations make up 19,595 observations and non-commercial stations, including dark stations, for 4,746 observations.

Table 13: TV station counts by power output and type of use and service (2012)

	Type of Use and Service						
	Commercial		Non-commercial				
	UHF	VHF	UHF	VHF	UHF	VHF	Total
Full-power							
Primary	950	292	281	104	1,231	396	1,627
Satellite	57	55	0	0	57	55	112
Low-power (Class-A)	376	42	8	1	384	43	427
Total	1,772		394		1,672	494	2,166

Notes: Only stations that are eligible for participation in the incentive auction included. Primary stations denote the owner's main station in the DMA. Satellite stations are full-power relay stations re-broadcasting for the primary stations. Non-commercial stations carry educational or public broadcast programming.

For commercial stations, advertising revenue is missing for 6,058, or 30.9%, station-year observations. Table 14 shows the share of station-year observations with missing advertising revenue for commercial stations. Advertising revenue is missing for almost all satellite stations because BIA subsumes a satellite's advertising revenue into that of its parent primary station.[37] Missing values are further concentrated among low-power (Class-A) stations, among stations affiliated with Spanish-language networks (Azteca America, Independent Spanish, Telemundo, Unimas, and Univision) and other minor networks, and among independent stations. There are no discernible patterns in missing values along other dimensions of the data such as the market size.

We impute advertising revenue for commercial stations where it is missing by regressing the log of advertising revenue (in \$ thousand) $\ln AD_{jt}$ on station, owner, and market characteristics X_{jt}. We run this regression separately for each year from 2003 to 2013 and use it to predict advertising revenue AD_{jt}. We include in X_{jt} the log of the station's population coverage (in thousand), an indicator for whether the TV station has multicast sub-channels, power output fixed effects (primary and class-A), fixed effects for the eleven affiliations in Table 14, fixed effects for the interaction of affiliation groups (see Section A.2.1) with U.S. states, an indicator for whether the owner owns more than one TV station in the same DMA, ownership category fixed effects (whether the owner owns one, between two and ten, or more than ten TV stations across DMAs), the number of TV stations in the DMA, the number of major network affiliates in the DMA, the wealth and competitiveness indices for the DMA (see Section A.2.1), and the log of the number of TV households (in thousand) in the DMA. Finally, we account for the contribution of any satellite stations to advertising revenue by including in X_{jt} the number of satellite stations that belong to the primary station N_{jt}^{SAT}.The adjusted R^2 is 0.99 in all years in logs and 0.75 on average in levels, suggesting that we capture most of the variation in advertising revenue across stations and years.

[37]We enforce this convention for the 36 station-year observations where a satellite has non-missing advertising revenue. We manually link satellite stations to their parent primary stations because BIA does not provide this information. The 114 satellite stations in Table 13 belong to 80 primary stations.

With the estimates in hand, we predict advertising revenue AD_{jt} as $\widehat{AD}_{jt} = e^{\ln \widehat{AD}_{jt} + \frac{\hat{\sigma}^2}{2}}$ to account for the non-zero mean of the log-normally distributed error term with estimated variance $\hat{\sigma}^2$. We proceed as follows: First, for a primary station we impute advertising revenue AD_{jt} where missing as $\widehat{AD}_{jt}$. Second, we compute the contribution of satellite stations (if any) to the advertising revenue of their parent primary station as $AD_{jt} - AD_{jt}/e^{\hat{\beta}_{SAT} N_{jt}^{SAT}}$, where $\hat{\beta}_{SAT}$ is the estimated coefficient for the number of satellite stations. For a primary station we net out the contribution of satellite stations by replacing advertising revenue AD_{jt} with $AD_{jt}/e^{\hat{\beta}_{SAT} N_{jt}^{SAT}}$. Third, for a satellite station we impute advertising revenue AD_{jt} by allocating the contribution of satellite stations to the advertising revenue of their parent primary station in proportion to the population coverage of the satellite stations.

Table 14: Missing advertising revenue for commercial stations

	Station-year count	Missing advertising revenue: Station-year count	Missing advertising revenue: %
Full-power			
Primary	13,490	937	6.95
Satellite	1,252	1,216	97.12
Low-power (Class-A)	4,853	3,905	80.47
Major networks			
ABC	2,497	420	16.82
CBS	2,423	314	12.96
Fox	2,272	318	14.00
NBC	2,445	376	15.38
Minor networks			
CW	850	99	11.65
MyNetwork TV	745	133	17.85
United Paramount	269	37	13.75
Warner Bros	267	24	8.99
Spanish-language networks	1,747	563	32.23
Other	3,159	1,781	56.38
Independent	2,921	1,993	68.23
Total	19,595	6,058	30.92

Notes: United Paramount and Warner Bros merged in 2006 to form CW. Spanish-language networks include Azteca America, Telemundo, Univision, UniMas, and Independent Spanish stations.

A.1.4 NAB data

NAB collects detailed financial information for commercial full-power stations. In 2012, NAB received 785 responses on 1,288 originated questionnaires, corresponding to a response rate of 60.9%.

NAB reports the data at various levels of aggregation. Table 15 shows the resulting 66 tables for 2012.[38] The number of tables fluctuates slightly year-by-year because NAB imposes a minimum of ten TV stations per aggregation category to ensure confidentiality.[39] Note that a TV station may feature in more than one table. For example, WABC-TV is the ABC affiliate in New York, NY. Its data is used in calculating statistics for (1) markets of rank 1 to 10; (2) major network affiliates; (3) all ABC affiliates; and (4) ABC affiliates in markets with rank 1 to 25.

For each aggregation category, NAB reports the mean, 1^{st}, 2^{nd}, and 3^{rd} quartiles for cash flow and detailed revenue source categories. We define non-broadcast revenue as the sum of total trade-outs and barter, multicast revenue, and other broadcast related revenue. We further define advertising revenue as the sum of local, regional, national, and political advertising revenues, commissions, and network compensations. Because we do not observe correlations between the detailed revenue source categories, we can construct the mean of non-broadcast revenue and advertising revenue but not the quartiles. We present sample moments of cash flow and non-broadcast revenue for select aggregation categories in Table 16.[40]

A.2 Cash flows

A.2.1 Functional forms

We parameterize $\alpha(X_{jt};\beta)$, $RT(X_{jt};\gamma)$, and $F(X_{jt};\delta)$ as a function of station and market characteristics X_{jt} as

$$\begin{aligned}
\alpha(X_{jt};\beta) =& \sum_{a=1}^{9} \beta_0^a I(\mathit{Affiliation}_{jt} = a) + \sum_{s=2003}^{2012} \beta_0^s I(t=s) + \beta_1 Fox_{jt}\cdot t + \beta_2 CompIndex_{jt},\\
RT(X_{jt};\gamma) =& \exp\left(\gamma_0 + \gamma_1 t + \gamma_2 \ln(MktSize_{jt})\right),\\
F(X_{jt};\delta) =& \delta_0 + \delta_1\, \mathit{WealthIndex}_{jt} + \sum_{h=1}^{3} I(\mathit{Group}_{jt}=h)\cdot\left(\delta_2^h \ln(MktSize_{jt}) + \delta_3^h \ln(MktSize_{jt})^2\right),
\end{aligned}$$

where $I(\cdot)$ is the indicator function. $Affiliation_{jt}$ refers to nine of the eleven affiliations[41] in Table 14 and $Group_{jt}$ to groupings of affiliations (detailed below). $MktSize_{jt}$ is the number of TV households in the DMA and $WealthIndex_{jt}$ and $CompIndex_{jt}$ are the wealth and competitiveness indices for the DMA.[42]

[38] We exclude 15 aggregation categories that are defined by total revenue from each year's NAB report because the BIA data is restricted to advertising revenue.

[39] Some years, in particular, break out United Paramount and Spanish-language networks but not other minor networks. We conclude that the response rate of other minor networks is very low and thus exclude other minor networks from most of the subsequent analysis.

[40] To validate the data, we compare the mean of advertising revenue from the NAB data to suitably averaged advertising revenue from the BIA data. The resulting 662 pairs of means from the two data sources exhibit a correlation of 0.92.

[41] We normalize the parameter on the indicator for Spanish-language networks to zero. We exclude any TV station affiliated with other minor networks from the estimation, see footnote 39. To predict the cash flow for such a TV station from our parameter estimates, we use its station and owner characteristics X_{jt} and the parameter on the indicator for Independent.

[42] To parsimoniously capture market characteristics, we conduct a principal component analysis of the market-level variables prime-age (18-54) population, average disposable income, retail expenditures, advertising revenues,

Table 15: NAB Tables (2012)

Table	Description	Table	Description
1	All Stations, All Markets	34	ABC, CBS, FOX, NBC, Markets 176+
2	All Stations, Markets 1-10	35	ABC, All Markets
3	All Stations, Markets 11-20	36	ABC, Markets 1-25
4	All Stations, Markets 21-30	37	ABC, Markets 26-50
5	All Stations, Markets 31-40	38	ABC, Markets 51-75
6	All Stations, Markets 41-50	39	ABC, Markets 76-100
7	All Stations, Markets 51-60	40	ABC, Markets 101+
8	All Stations, Markets 61-70	41	CBS, All Markets
9	All Stations, Markets 71-80	42	CBS, Markets 1-25
10	All Stations, Markets 81-90	43	CBS, Markets 26-50
11	All Stations, Markets 91-100	44	CBS, Markets 51-75
12	All Stations, Markets 101-110	45	CBS, Markets 76-100
13	All Stations, Markets 111-120	46	CBS, Markets 101+
14	All Stations, Markets 121-130	47	FOX, All Markets
15	All Stations, Markets 131-150	48	FOX, Markets 1-50
16	All Stations, Markets 151-175	49	FOX, Markets 51-75
17	All Stations, Markets 176+	50	FOX, Markets 76-100
18	ABC, CBS, FOX, NBC, All Markets	51	FOX, Markets 101+
19	ABC, CBS, FOX, NBC, Markets 1-10	52	NBC, All Markets
20	ABC, CBS, FOX, NBC, Markets 11-20	53	NBC, Markets 1-25
21	ABC, CBS, FOX, NBC, Markets 21-30	54	NBC, Markets 26-50
22	ABC, CBS, FOX, NBC, Markets 31-40	55	NBC, Markets 51-75
23	ABC, CBS, FOX, NBC, Markets 41-50	56	NBC, Markets 76-100
24	ABC, CBS, FOX, NBC, Markets 51-60	57	NBC, Markets 101+
25	ABC, CBS, FOX, NBC, Markets 61-70	58	CW, All Markets
26	ABC, CBS, FOX, NBC, Markets 71-80	59	CW, Markets 1-25
27	ABC, CBS, FOX, NBC, Markets 81-90	60	CW, Markets 26-50
28	ABC, CBS, FOX, NBC, Markets 91-100	61	CW, Markets 51-75
29	ABC, CBS, FOX, NBC, Markets 101-110	62	MNTV, All Markets
30	ABC, CBS, FOX, NBC, Markets 111-120	63	MNTV, Markets 1-50
31	ABC, CBS, FOX, NBC, Markets 121-130	64	MNTV, Markets 51+
32	ABC, CBS, FOX, NBC, Markets 131-150	65	Independent, All markets
33	ABC, CBS, FOX, NBC, Markets 151-175	66	Independent, Markets 1-25

Notes: Data comes from NAB annual directory for 2012. Market numbers refer to a market's rank in terms of size. NAB rules prohibit aggregation when there are too few respondents in a particular grouping, which determines the market size ranges. Tables with total revenue breakouts are excluded.

Table 16: Sample moments for cash flow and non-broadcast revenue for select aggregation categories (2012)

	Cash Flow ($ million)				Non-broadcast Revenue ($ million)
		Percentile			
	Mean	25th	50th	75th	Mean
All Stations	7.798	1.243	3.752	9.178	2.977
All Stations, Markets 101-110	4.120	1.704	3.619	6.444	2.102
All Major Affiliates	9.244	1.936	4.929	10.901	3.326
ABC Affiliates, Markets 1-25	32.400	15.090	27.150	42.460	7.596
NBC Affiliates, Markets 101+	3.652	1.293	3.283	5.901	1.883
All CW Affiliates	3.929	0.355	1.798	3.224	2.884
MyNetwork TV Affiliates, Markets 1-50	3.124	1.270	1.799	3.215	2.507
All Independent Stations	2.786	-0.020	1.288	4.327	2.195

Notes: Data comes from NAB annual directory for 2012. A select few categories are reported (see Table 15 for all categories). Non-broadcast revenues are constructed as the sum of total trade-outs and barter, multicast revenues, and other broadcast related revenues. We thus only obtain the mean as we lack information on the correlations of the respective distributions.

We allow the share $\alpha(X_{jt};\beta)$ of advertising revenue retained as cash flow to vary flexibly by year and network affiliation. We allow for a separate time trend for Fox affiliates as their profitability grew substantially over time. The competitiveness index $CompIndex_{jt}$ accounts for differences in the competitive environment across DMAs.

We specify $RT(X_{jt};\gamma)$ as an exponential function of a time trend and market size in light of the rapid growth of retransmission fees. We make no attempt to separately estimate an error term for non-broadcast revenue and assume it is one part of ϵ_{jt} in equation 6 due to additivity.[43]

Lastly, we let fixed cost $F(X_{jt};\delta)$ vary flexibly with market size and the network affiliation. To streamline the specification, we subsume the affiliations in Table 14 into three groups with similar cost structures: (1) ABC, CBS, and NBC; (2) Fox, CW, and Warner Bros; (3) My Network TV, United Paramount, Spanish-language networks, and Independents. We include the wealth index $WealthIndex_{jt}$ in the fixed cost to reflect the differential cost of operating in different DMAs.

A.2.2 Data

We combine the station-level data on advertising revenue from BIA with the aggregated data from NAB. The NAB data yields 3,313 moments across aggregation categories and the years from 2003 to 2012 as shown in Table 18.[44] There are a total of 11,801 station-year observations from the BIA data that meet NAB's data collection and reporting procedure and therefore map into a table of a

number of primary TV stations, and number of major network affiliates. The first principal component, denoted as $CompIndex_{jt}$, loads primarily on to prime-age population, advertising revenues, number of primary TV stations, and number of major network affiliates. The second principal component, denoted as $WealthIndex_{jt}$ loads primarily on to average disposable income and retail expenditures.

[43]We obtain very similar estimates when we separately estimate such an error term.

[44]We drop the year 2013 from the BIA data as 2012 is the latest year of availability for the NAB data. We further drop TV stations affiliated with other minor networks from the BIA data, see footnotes 39 and 41.

NAB report.

A.2.3 Estimation

We use a simulated minimum distance estimator. We draw $S = 100$ vectors of cash flow error terms $\epsilon^s = \left(\epsilon^s_{jt}\right)$, where ϵ^s_{jt} is the cash flow error term of TV station j in year t in draw s. Denote by $\overline{CF}_{gt}$, CF^1_{gt}, CF^2_{gt}, and CF^3_{gt} the mean, 1^{st}, 2^{nd}, and 3^{rd} quartiles of the cash flow distribution reported by NAB in year t for aggregation category $g = 1, \ldots, G_t$, where G_t is the number of aggregation categories in year t. Similarly, denote by $\widehat{\overline{CF}}_{gt}(\theta;\epsilon^s)$, $\widehat{CF}^1_{gt}(\theta;\epsilon^s)$, $\widehat{CF}^2_{gt}(\theta;\epsilon^s)$, and $\widehat{CF}^3_{gt}(\theta;\epsilon^s)$ the analogous moments of the predicted cash flow distribution for the TV stations that feature in aggregation category g in year t. Our notation emphasizes that the latter depend on the parameters $\theta = (\beta, \gamma, \delta, \sigma)$ and the vector of cash flow error terms ϵ^s in draw s. We use similar notation, replacing $\overline{CF}$ with $\overline{RT}$, for the mean of the non-broadcast revenue distributions. To estimate θ, we match the moments of the predicted and actual distributions across aggregation categories and years. Formally,

$$\hat{\theta} = \arg\min_{\theta} \sum_{t=2003}^{2012} \sum_{g=1}^{G_t} \left(\overline{CF}_{gt} - \frac{1}{S}\sum_{s=1}^{S} \widehat{\overline{CF}}_{gt}(\theta;\epsilon^s) \right)^2 + \sum_{q=1}^{3} \left(CF^q_{gt} - \frac{1}{S}\sum_{s=1}^{S} \widehat{CF}^q_{gt}(\theta;\epsilon^s) \right)^2 + \left(\overline{RT}_{gt} - \widehat{\overline{RT}}_{gt}(\theta) \right)^2 .$$

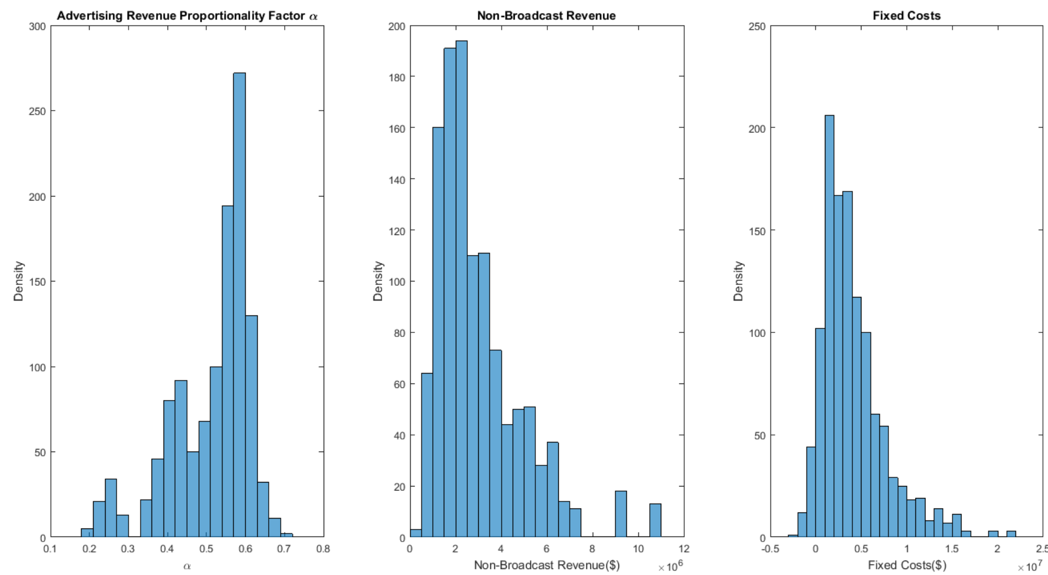
We constrain the standard deviation of the error term to be positive. Our interior-point minimization algorithm terminates with a search step less than the specified tolerance of 10^{-12}. We use multi starts to guard against local minima. Our estimates are robust to different starting values.

A.2.4 Results

Table 17 reports the parameter estimates. The estimates are in line with our expectations: major network affiliates retain a higher share of advertising revenue than minor networks, with Fox having a positive trend; independent and WB stations retain the highest share of advertising revenues, albeit with the smallest revenue base; the retained share falls over time, bottoming out in 2009 before bouncing back in recent years; the retained share is lower in more competitive markets. Finally, non-broadcast revenue has grown significantly in recent years and there are economies of scale in fixed cost.

Figure 9 plots the distributions of the estimated retained share $\alpha(X_{jt};\beta)$, non-broadcast revenue $RT(X_{jt};\delta)$, and fixed cost $F(X_{jt};\delta)$. Reassuringly, without imposing restrictions, we estimate α to be between 0.2 and 0.7 in 2012, with an average of 0.51; non-broadcast revenue is estimated to be between \$0.21 million and \$10.9 million; fixed cost is estimated to be contributing negatively to cash flow in 95% of cases, averaging \$4.12 million, with the highest fixed cost estimated to be up to \$21.9 million in 2012.

Figure 9: Estimated Retained Share of Advertising Revenue $\alpha(X_{jt};\beta)$, Non-Broadcast Revenue $RT(X_{jt};\delta)$, and Fixed Cost $F(X_{jt};\delta)$ (2012)



Notes: Plots are distributions of estimated retained share of advertising revenue α (left), non-broadcast revenue in dollars (middle), and fixed cost in dollars (right) in 2012. Includes 1,172 commercial full-power stations in 2012 used in the cash flow estimation.

Table 17: Cash Flow Parameters Estimates

	Estimates
Retained share $\alpha(X_{jt};\beta)$ of advertising revenue	
ABC	-0.035
CBS	-0.062
Fox	-0.382
NBC	-0.054
CW	-0.113
MyNetwork TV	-0.356
United Paramount	-0.364
Warner Bros	0.013
Spanish-language networks (normalized)	0
Independent	-0.210
Fox × Trend	0.018
2003	0.692
2004	0.666
2005	0.642
2006	0.630
2007	0.599
2008	0.567
2009	0.529
2010	0.600
2011	0.619
2012	0.636
$CompIndex$	-0.021
Non-broadcast revenue $RT(X_{jt},\gamma)$ (log \$)	
Intercept	6.513
ln(MktSize)	0.527
Trend	0.135
Fixed cost $F(X_{jt};\delta)$ (\$ million)	
Intercept	63.941
$WealthIndex$	1.052
Group 1 × ln(MktSize)	-12.851
Group 2 × ln(MktSize)	-11.696
Group 3 × ln(MktSize)	-10.210
Group 1 × ln(MktSize)^2	0.643
Group 2 × ln(MktSize)^2	0.535
Group 3 × ln(MktSize)^2	0.419
σ (\$ million)	1.030

Notes: Group 1 is ABC, CBS, and NBC; group 2 is Fox, CW, and Warner Bros; and group 3 is My Network TV, United Paramount, Spanish-language networks, and Independents.

The cash flow model fits the data well. Figure 10 plots the predicted distributions of cash flow and non-broadcast revenue, superimposed with the corresponding moments from the NAB data for all TV stations in 2012. Cash flow is estimated to be between -$6.4 million and $127 million across

Table 18: Cash Flow and Non-Broadcast Revenue Moments and Fit Measures

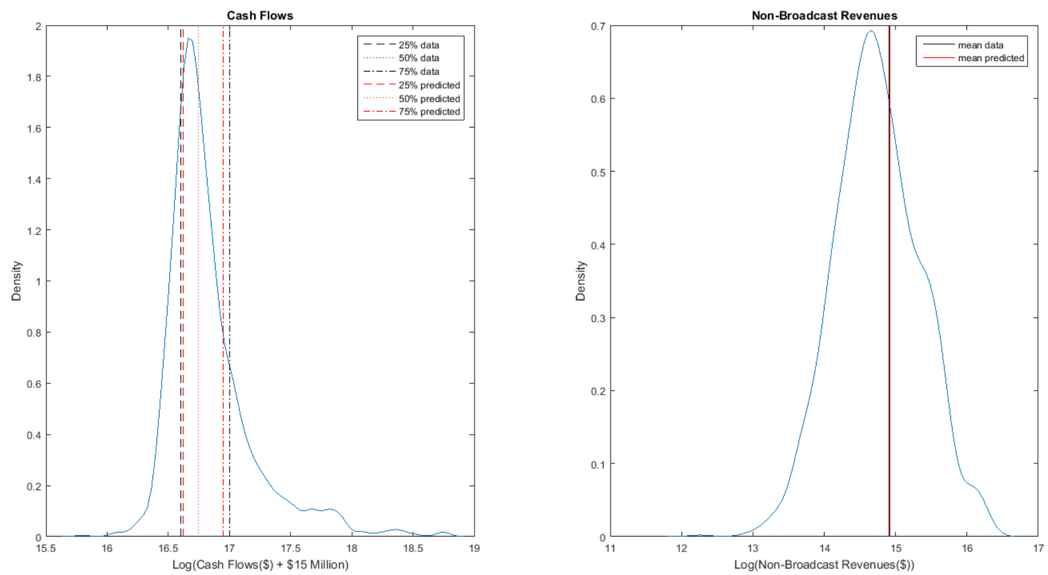
		Number of Moments	Correlation	Mean Abs Deviation $ million	Mean Abs Deviation %
All		3313	0.98	0.91	18.11
Type	Cash flow, mean	663	0.99	0.89	13.16
	1^{st} quartile	662	0.97	0.90	35.24
	2^{nd} quartile	663	0.98	0.90	17.73
	3^{rd} quartile	663	0.98	1.36	15.16
	Non-broadcast revenue, mean	662	0.84	0.49	28.65
Affiliation	Major network	1995	0.98	1.00	16.13
	Minor network	350	0.93	1.00	38.55
	Independent	110	0.73	0.95	62.31
Year	2003	329	0.98	1.03	19.52
	2004	325	0.99	0.87	15.05
	2005	330	0.98	0.95	19.17
	2006	310	0.99	0.96	16.26
	2007	344	0.98	0.90	19.68
	2008	350	0.98	0.86	20.43
	2009	330	0.98	0.66	23.08
	2010	330	0.98	0.84	16.30
	2011	335	0.97	0.90	18.68
	2012	330	0.98	1.11	16.51
Market Rank	1-25	460	0.98	2.37	14.74
	26-50	385	0.96	0.94	15.97
	51-100	930	0.93	0.63	19.98
	101+	799	0.87	0.47	32.21

Notes: Correlations refer to correlations between predicted and observed dollar magnitudes for a particular subsample of distribution moments. Percent mean deviations measured as a share of observed dollar magnitudes.

TV stations in 2012, with an average of $7.2 million (compared to $7.8 million reported by NAB). The 25^{th} ($1.6 million), 50^{th} ($3.6 million), and 75^{th} ($7.8 million) percentiles of the predicted distribution are overlaid in red lines (dashed, dotted, and dash-dotted, respectively). The black lines of the same patterns refer to the corresponding moments in the NAB data. Non-broadcast revenue is estimated to average $3.0 million (compared to $3.0 million reported by NAB).

To further assess the fit of the cash flow model, Table 18 compares the cash flow and non-broadcast revenue moments as reported in NAB to the corresponding predicted moments, broken down type of moment, affiliation, year, and market rank. It provides three different measures of fit, namely the correlation between actual and predicted moments as well as the absolute deviation in millions of dollars and in percent magnitudes, and percent of absolute deviations. Overall, our cash flow model predicts the 3,313 moments with a 0.98 correlation. Of the 330 moments from 2012, our predicted moments have a 0.98 correlation with the actual moments reported by NAB; on average, our predicted moments miss the actual moments by $1.11 million, or 16.5%.

Figure 10: Estimated Cash Flow and Non-Broadcast Revenue with Moments (2012)



Notes: Plots are kernel densities of estimated cash flows (left) and non-broadcast revenues (right) in 2012 in log terms. Cash flows (in dollars) are shifted by $15 million to avoid negative numbers. Black lines indicate data moments and red lines indicate model-predicted moments. Data moments are from the all-station category in NAB (year 2012, table 1). Includes 1,172 commercial full power stations in 2012 used in the cash flow estimation procedure. The cash flow distribution is plotted from one simulation with station-specific errors.

A.3 Multiples

A.3.1 Priors

Industry analysts give a range of \$0.15 to \$0.40 per MHz-pop for the stick multiple and a range of 10 to 12 for the cash flow multiple.[45] Therefore, our prior is that the stick multiple is distributed log-normally with mean $\mu_{prior}^{Stick} = -1.4$ and standard deviation $\sigma_{prior}^{Stick} = 0.5$ (corresponding to a mean of \$0.25 per MHz-pop and a standard deviation of \$1 per MHz-pop, thereby covering \$0.15 to \$0.40 per MHz-pop with probability 0.68). According to industry analysts, while the stick multiple is believed to be much larger for larger markets, the cash flow multiple is believed to be symmetrically distributed. Our prior is therefore that the cash flow multiple is distributed normally with mean $\mu_{prior}^{CF} = 11$ and standard deviation $\sigma_{prior}^{CF} = 1$.

A.3.2 Data

As discussed in Section 4.1, our data consists of 136 transactions between 2003 and 2012 based on cash flow and 201 transactions between 2003 and 2013 based on stick value. For cash flow transactions, we infer the cash flow multiple from the transaction price and the estimated cash flow $\widehat{CF}_{jt}$ using equation 4. For stick value transactions, we infer the stick multiple from the transaction price using equation 5.

A.3.3 Estimation

For cash flow transactions, we estimate the following model for the multiple to construct its conditional likelihood function:

$$Multiple_{jt}^{CF} = \beta X_{jt} + \epsilon_{jt}, \tag{7}$$

where X_{jt} includes owner, station, and market characteristics. Specifically, we include in X_{jt} an indicator of whether a station has multicast sub-channels, the station's population coverage (in thousand), the wealth and competitiveness indices for the DMA, power output fixed effects (primary, satellite, and class-A), ownership category fixed effects (whether the owner owns one, between two and ten, or more than ten stations across markets), fixed effects for the eleven affiliations in Table 14, and a full set of year fixed effects. The adjusted R^2 is 0.68 and we take $\hat{\sigma}_{likelihood}^{CF} = 4.52$ to be the standard deviation of the 136 estimated residuals.

For stick value transactions, we estimate the following model:

$$\ln Multiple_{jt}^{Stick} = \beta X_{jt} + \epsilon_{jt}, \tag{8}$$

[45] See "Opportunities and Pitfalls on the Road to the Television Spectrum Auction," Bond & Pecaro white paper, December 12, 2013, available at http://www.bondpecaro.com/images/Bond_Pecaro_Spectrum_White_Paper_12122013.pdf, accessed on November 15, 2015.

where we include in X_{jt} the log of the station's output power, the log of the station's population coverage, the wealth and competitiveness indices for the DMA, power output fixed effects, ownership category fixed effects, affiliation fixed effects, and year fixed effects. The adjusted R^2 is 0.67 and we take $\hat{\sigma}^{Stick}_{likelihood} = 0.97$.

A.3.4 Posteriors

With the estimates in hand, we can predict multiples for any TV stations. To obtain the posterior for the cash flow, respectively, stick multiple, we update our prior with the conditional likelihood function using Bayes rule as

$$\mu_{posterior} = \frac{\mu_{prior}\sigma^2_{likelihood} + \mu_{likelihood}\sigma^2_{prior}}{\sigma^2_{prior} + \sigma^2_{likelihood}},$$

$$\sigma^2_{posterior} = \frac{\sigma^2_{likelihood}\sigma^2_{prior}}{\sigma^2_{prior} + \sigma^2_{likelihood}},$$

where $\mu^{CF}_{likelihood} = \widehat{Multiple}^{CF}_{jt_0}$ for cash flow transactions and $\mu^{Stick}_{likelihood} = \ln \widehat{Multiple}^{Stick}_{jt_0}$ for stick value transactions and we set $t_0 = 2012$. The posterior standard deviation of the cash flow multiple is 0.98 and that of the stick multiple is 0.44. Because the posterior mean depends on X_{jt}, Figure 11 illustrates the estimated posterior distribution for the cash flow, respectively, stick multiple in one particular simulation run for the 1,672 UHF licenses that the FCC includes in its repacking simulations. The prior distributions are overlaid in red dashed lines.

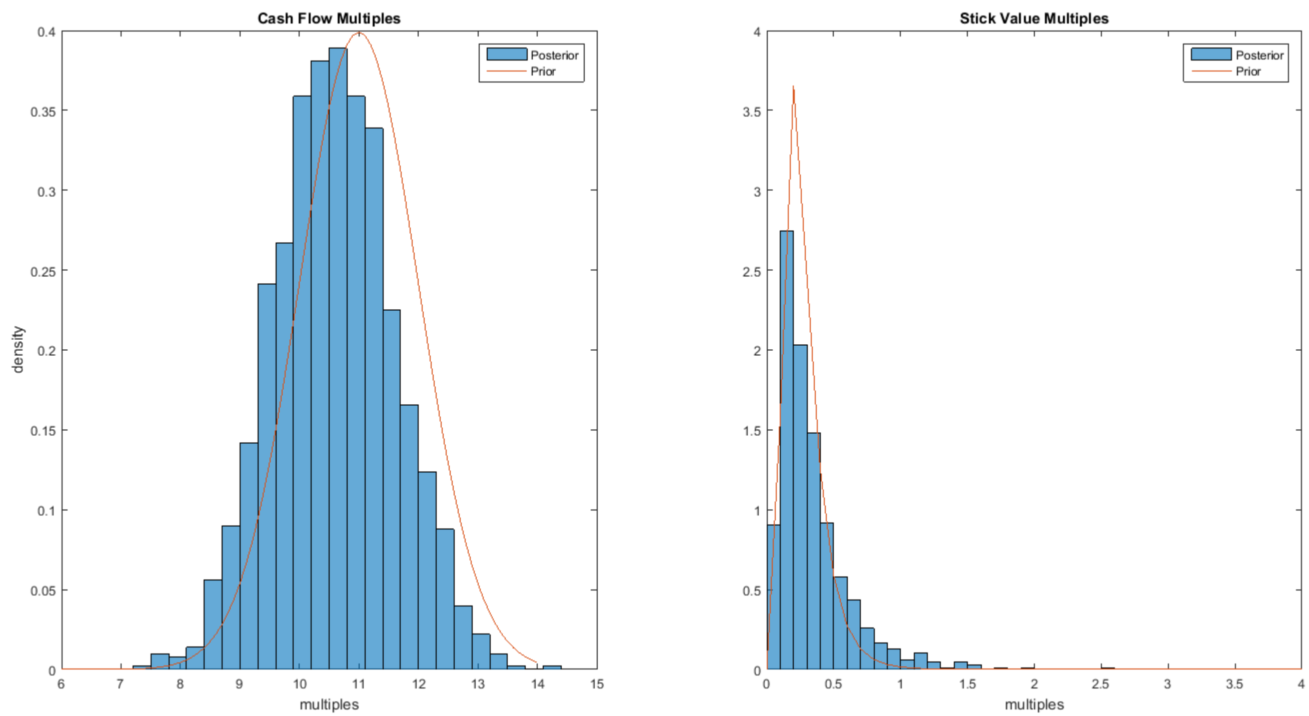
B Algorithm details

There are N TV stations in the focal DMA and the DMAs in its repacking region. As in section 2.2, denote as v_j the reservation value of TV station j and asφ_j station j's broadcast volume. We order TV stations such that $\frac{v_1}{\varphi_1} \leq \frac{v_2}{\varphi_2} \leq \ldots \leq \frac{v_N}{\varphi_N}$. Breaking ties in favor of selling, we have that if the base clock price P exceeds $\frac{v_N}{\varphi_N}$, then all stations $1, \ldots, N$ would be willing to relinquish their license. If the base clock price is $\frac{v_N}{\varphi_N} > P \geq \frac{v_{N-1}}{\varphi_{N-1}}$, then only stations $1, \ldots, N-1$ relinquish their license, while station N prefers to continue operating and drops out of the auction, at which point it has to be repacked, and so on.

A given clearing target of spectrum maps into a certain number of TV station channels to be cleared for wireless service. For example, the auction's initial 126 MHz clearing target would have corresponded to clearing 21 channels out of a total of 37 non-dedicated UHF channels in each DMA. In some DMAs, this would be possible without purchasing spectrum from TV stations since not all channels are allocated. Denote the channels available for repacking TV stations that choose to continue operating after the reverse auction by R. For simplicity, we suppress the dependency of R on the spectrum clearing target.

The repacking feasibility checker SATFC takes as inputs the remaining available channels R and a set of TV stations X, together with their interference profile and the channels to which they could

Figure 11: Prior and Posterior Distributions of Cash Flow Multiple and Stick Multiple



Notes: Probability density function for the prior distributions and estimated posterior distributions. Plotted from one simulation (one station-specific draw for each station).

be repacked.[46] Denote this as $SATFC(X, R)$. It then returns one of three possible outcomes:SAT, $UNSAT$, or $TIMEOUT$. SAT denotes that the set of stations X could be satisfactorily repacked. $UNSAT$ indicates that is is not possible, leading to a station being frozen, while $TIMEOUT$ indicates that within the maximum amount of time allotted to one run of the feasibility checker, it was not possible to ascertain whether repacking would be feasible. Based on testing, the FCC has set set the TIMEOUT parameter to one minute, which we also use. Their testing found that this time limit offered an efficient trade off between total computational burden and accuracy, and interpret TIMEOUT as an UNSAT.

We partition the set of TV stations $\{1, \dots, N\}$ into a set of "active" stations A, a set of "frozen" (or "conditionally winning") stations F, and a set of "inactive"stations I that, given the initial clock price $P = 900$ immediate drop out of the auction (see Competitive Bidding Procedures for Broadcast Incentive Auction 1000, Including Auctions 1001 and 1002, Public Notice FCC 14-191, p. 105, available at https://www.fcc.gov/document/broadcast-incentive-auction-comment-pn).

Finally, denote as PO_j the payout to TV station j from the reverse auction, expressed in terms of the base clock price; the station's ultimate selling price would be $\varphi_j PO_j$. We iteratively solve the reverse auction in Matlab interfacing with SATFC via a Java bridge. To initialize, we set $P = 900$, and define the set of active stations $A = \left\{s \in \{1, \dots, N\} | \frac{v_s}{\varphi_s} \leq 900\right\}$, the set of frozen stations $F = \emptyset$, and the set of inactive stations $I = \left\{s \in \{1, \dots, N\} | \frac{v_s}{\varphi_s} > 900\right\}$. That is, all TV stations with valuation less than or equal to 900 participate in the reverse auction. If $SATFC(I, R) \neq SAT$, then the remaining stations cannot be repacked. In this case, we declare the auction as failed and set $PO_s = 0$ for all $s \in \{1, \dots, N\}$.

Otherwise, we proceed as follows:

1. REPEAT
   (a) For each $s \in A$ run $SATFC(I \cup \{s\}, R)$.
      i. If $SATFC(I \cup \{s\}, R) = UNSAT$, station s cannot be repacked. Change its status to frozen: set $A \leftarrow A \setminus \{s\}$, $F \leftarrow F \cup \{s\}$. Its payout is the current base clock price: $PO_s = P$.
   (b) If $A \neq \emptyset$ then set $s = \max_{s \in A}(\frac{v_s}{\varphi_s})$, $P = \frac{v_s}{\varphi_s}$, $A \leftarrow A \setminus \{s\}$, $I \leftarrow I \cup \{s\}$, and $PO_s = 0$.
2. UNTIL $A = \emptyset$

Step (i) changes the status of any currently active TV station that cannot be repacked in addition to the currently inactive TV stations to frozen (p. 108 and pp. 112–113, FCC 14-191). If a TV station is frozen, it receives a payout equal to the current base clock price P. P, in turn, is determined by the TV station most recently marked as inactive (or, possibly, the opening base clock price of 900).

At the end of steps (a)–(b) we are guaranteed that changing the status of any remaining active TV station to inactive preserves feasibility. Step (c) then finds the remaining active TV station

[46] We use Perl scripts to create repacking region-specific domain and interference files to use with the SATFC feasibility checker to simulate the auction. This speeds up computation and decreases the amount of memory overhead required for large-scale parallel computing.

with the highest value and changes its status from active to inactive. This TV station receives a payout of zero.

B.1 Illustration

Figure 12: Simulation Algorithm Examples

DMA: 4, Simulation: 7, Strategy: 1
126 Total Licenses Considered, 23 in Focal DMA

Processing Withdrawls.

1: #9610 (CBS) withdraws…✓
2: #47535 (NBC) withdraws…✓
3: #22206 (FOX) withdraws…✓
4: #47904 (NBC) withdraws…✓
5: #15569 (NBC) withdraws…✓
6: #70158 (IND) withdraws…✓
7: #68136 (IND) withdraws…✓

Auction begins.

8: #68135 (IND) withdraws at $873.34…✓
9: #22207 (FOX) withdraws at $748.20…✓
10: #52077 (FOX) withdraws at $667.83…✓
11: #53115 (CBS) withdraws at $639.13…✓
12: #25453 (CBS) withdraws at $626.80…✓
13: #4688 (ABC) withdraws at $476.46…✓
14: #51568 (FOX) withdraws at $463.92…✓
15: #63153 (NBC) withdraws at $444.89…✓
16: #23341 (CBS) withdraws at $443.64…✓
17: #60653 (NBC) withdraws at $427.76…✓
18: #74215 (UNI) withdraws at $422.03…✓
19: #71218 (CBS) withdraws at $400.52…✓
20: #73318 (ABC) withdraws at $365.24…✓
21: #50780 (NBC) withdraws at $357.84…✓
22: #74170 (NBC) withdraws at $323.50…✓
23: #73333 (TEL) withdraws at $298.15…✗
➢ **#39884 (IND) frozen at $298.15**
24: #10213 (FOX) withdraws at $254.81…✓
25: #147 (FOX) withdraws at $242.21…✓
26: #62219 (FOX) withdraws at $241.57…✓
27: #13929 (REL) withdraws at $235.37…✓
28: #191822 (OTH) withdraws at $229.57…✓
29: #73120 (NBC) withdraws at $228.28…✓
30: #72278 (IND) withdraws at $224.06…✓
31: #74197 (MY) withdraws at $221.79…✗
➢ **#60560 (UNI) frozen at $221.79**
➢ **#74464 (Am1) frozen at $221.79**
➢ **#12499 (CW) frozen at $221.79**
➢ **#55305 (IND) frozen at $221.79**
➢ **#7623 (TBN) frozen at $221.79**
➢ **#51984 (ION) frozen at $221.79**
➢ **#48465 (PBS) frozen at $221.79**
➢ **#23142 (TEL) frozen at $221.79**
➢ **#191340 (OTH) frozen at $221.79**
➢ **#28480 (PUB) frozen at $221.79**
➢ **#36989 (PBS) frozen at $221.79**
➢ **#48481 (PBS) frozen at $221.79**
32: #10758 (FOX) withdraws at $208.75…✓
33: #52075 (MY) withdraws at $206.82…✓
34: #167543 (MdF) withdraws at $201.53…✓
35: #50357 (OTH) withdraws at $175.93…✓
36: #30576 (CW) withdraws at $172.90…✓
37: #11260 (ABC) withdraws at $170.23…✓
38: #190915 (FOX) withdraws at $151.07…✓
39: #72313 (CBS) withdraws at $149.28…✓
40: #73879 (MY) withdraws at $148.81…✓
41: #51567 (MY) withdraws at $144.80…✓
42: #20287 (ABC) withdraws at $137.30…✓
43: #71508 (ABC) withdraws at $127.85…✓
44: #73374 (CW) withdraws at $124.65…✓
45: #70493 (ME) withdraws at $100.53…✗
➢ **#9739 (IND) frozen at $100.53**
46: #16455 (ABC) withdraws at $98.56…✓
47: #72623 (OTH) withdraws at $93.75…✓
48: #50063 (ION) withdraws at $83.70…✓
49: #74216 (UnM) withdraws at $72.66…✗
➢ **#61111 (NBC) frozen at $72.66**

Simulation concludes as all licenses in the focal DMA have either been withdrawn or frozen.

DMA: 4, Simulation: 7, Strategy: 325
126 Total Licenses Considered, 23 in Focal DMA

Processing Withdrawls.

1: #9610 (CBS) withdraws…✓
2: #47535 (NBC) withdraws…✓
3: #22206 (FOX) withdraws…✓
4: #47904 (NBC) withdraws…✓
5: #15569 (NBC) withdraws…✓
6: #70158 (IND) withdraws…✓
7: #74464 (Am1) withdraws…✓
8: #68136 (IND) withdraws…✓
9: #72278 (IND) withdraws…✓

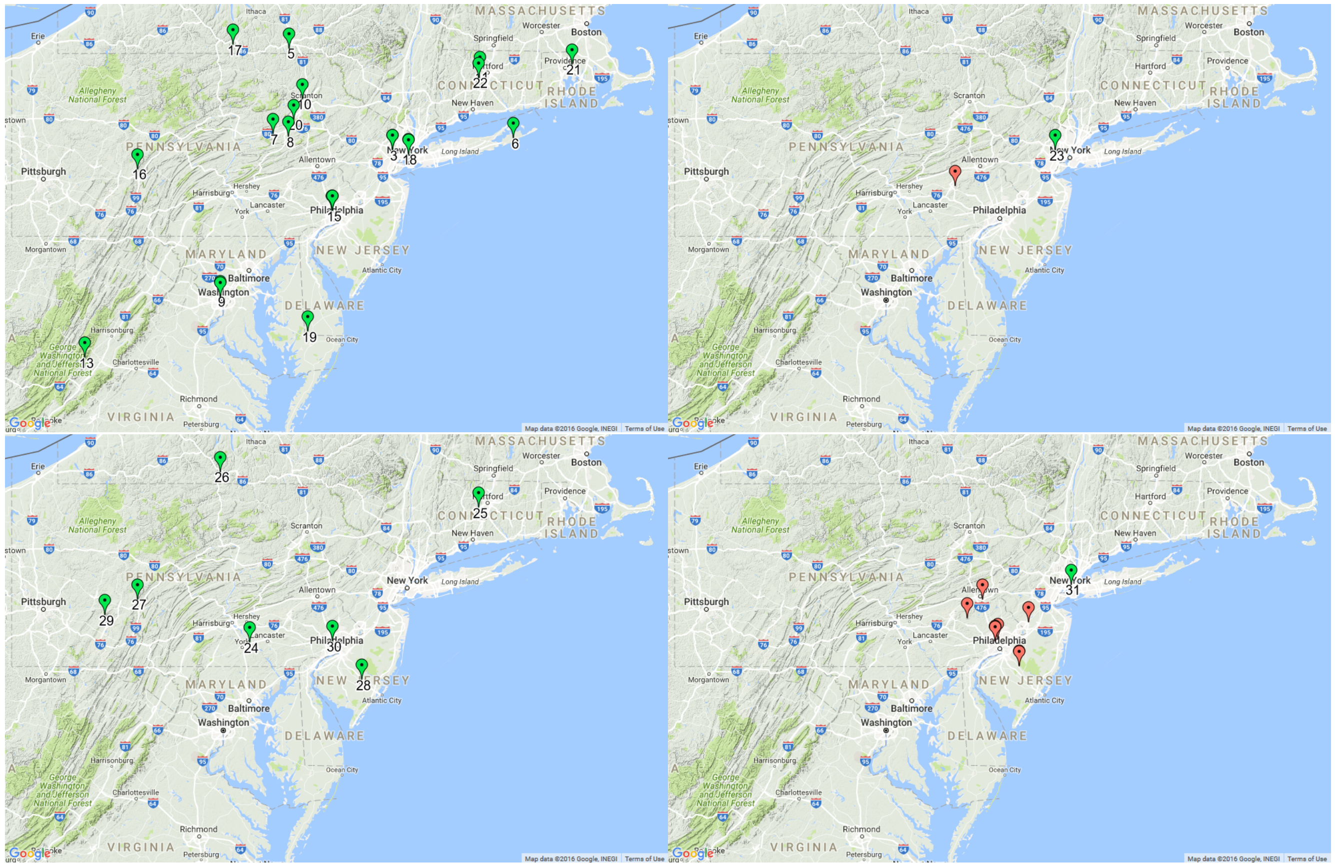
Auction begins.

10: #68135 (IND) withdraws at $873.34…✓
11: #22207 (FOX) withdraws at $748.20…✓
12: #52077 (FOX) withdraws at $667.83…✓
13: #53115 (CBS) withdraws at $639.13…✓
14: #25453 (CBS) withdraws at $626.80…✓
15: #4688 (ABC) withdraws at $476.46…✓
16: #51568 (FOX) withdraws at $463.92…✓
17: #63153 (NBC) withdraws at $444.89…✗
➢ **#39884 (IND) frozen at $444.89**
18: #23341 (CBS) withdraws at $443.64…✓
19: #60653 (NBC) withdraws at $427.76…✓
20: #74215 (UNI) withdraws at $422.03…✓
21: #71218 (CBS) withdraws at $400.52…✓
22: #73318 (ABC) withdraws at $365.24…✓
23: #50780 (NBC) withdraws at $357.84…✓
24: #74170 (NBC) withdraws at $323.50…✓
25: #73333 (TEL) withdraws at $298.15…✗
➢ **#60560 (UNI) frozen at $298.15**
➢ **#12499 (CW) frozen at $298.15**
➢ **#55305 (IND) frozen at $298.15**
➢ **#7623 (TBN) frozen at $298.15**
➢ **#51984 (ION) frozen at $298.15**
➢ **#48465 (PBS) frozen at $298.15**
➢ **#23142 (TEL) frozen at $298.15**
➢ **#191340 (OTH) frozen at $298.15**
➢ **#28480 (PUB) frozen at $298.15**
➢ **#36989 (PBS) frozen at $298.15**
➢ **#48481 (PBS) frozen at $298.15**
26: #10213 (FOX) withdraws at $254.81…✗
➢ **#9739 (IND) frozen at $254.81**
27: #147 (FOX) withdraws at $242.21…✓
28: #62219 (FOX) withdraws at $241.57…✓
29: #13929 (REL) withdraws at $235.37…✓
30: #191822 (OTH) withdraws at $229.57…✓
31: #73120 (NBC) withdraws at $228.28…✓
32: #74197 (MY) withdraws at $221.79…✗
➢ **#167543 (MdF) frozen at $221.79**
➢ **#73879 (MY) frozen at $221.79**
➢ **#74216 (UnM) frozen at $221.79**
➢ **#61111 (NBC) frozen at $221.79**

Simulation concludes as all licenses in the focal DMA have either been withdrawn or frozen.

Notes: Checkmarks (✓) indicate that all remaining active stations can feasibly be repacked when the listed station withdraws. Crosses (✗) indicate that at least one active license can no longer feasibly be repacked when the listed station withdraws. Events concerning licenses in the focal DMA are in bold. Licenses are numbered by FCC ID numbers. Prices are in terms of the base clock price.

Figure 13: Simulation Algorithm Example Maps



Notes: Maps show condensed simulation process from Figure 12. Green pins denote stations that withdraw from the auction and are labeled with their rank in the order of station withdrawals. Red pins denote stations whose price is frozen because they can no longer be repacked given the green stations' withdrawals in prior rounds. The top left map shows that the first 22 withdrawals in the region are processed with no constraints violated. The 23rd leads to a station being frozen in the top right map. The bottom left map shows that withdrawals 24 through 30 are then processed without incident, but the bottom right shows that the 31st station withdrawing and being repacked leads to the price being frozen for a handful of other stations.