Ownership Concentration and Strategic Supply Reduction*

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Abstract

We explore the implications of ownership concentration for the recently-concluded incentive auction that re-purposed spectrum from broadcast TV to mobile broadband usage in the U.S. We document significant multi-license ownership of TV stations. We show that in the reverse auction, in which TV stations bid to relinquish their licenses, multi-license owners have an incentive to withhold some TV stations to drive up prices for their remaining TV stations. Using a large-scale valuation exercise, we find that this strategic supply reduction conservatively increases payouts to TV stations by between 13.5% and 42.4%.

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1 Introduction

In 2010, the Federal Communications Commission (henceforth FCC) proposed to acquire spectrum from broadcast TV license holders and sell it to wireless carriers to be re-purposed for mobile broadband usage. The ensuing incentive auction is the most novel auction designed since the inception of spectrum auctions in the U.S. in the 1990s. It combines a reverse auction, in which TV stations bid to relinquish their licenses in exchange for payment, with a forward auction, in which wireless carriers bid for spectrum. The incentive auction closed on March 30, 2017 and re-purposed 84 MHz of spectrum from broadcast TV to mobile broadband usage. It raised $19.6 billion from wireless carriers in the forward auction and paid $10.1 billion to TV stations in the reverse auction, with most of the overage going to the U.S. Treasury. In light of the social value of the re-purposed spectrum and the revenue it raised for the government, the incentive auction is regarded as a triumph of modern market design.

In this paper, we study the role of ownership concentration and strategic supply reduction in the reverse auction. We document that following the announcement of the incentive auction, a number of private equity firms acquired TV stations, often purchasing multiple TV stations in the same local media market. Newspaper articles and industry reports claimed that these purchases were undertaken with the goal of "flipping" the TV stations for profit in the reverse auction.[1] Politicians also raised concerns about speculation.[2] We further document that despite the attention the private equity firms received, they account for just a small fraction of the joint ownership of TV stations.

We argue that besides any possible speculative motives, ownership concentration gives rise to strategic bidding in the reverse auction. We show that owners of multiple TV stations have an incentive to withhold some of their TV stations from the reverse auction, thereby driving up the prices for the remaining TV stations they own. This strategy of reducing supply affects a large transfer of wealth from the government—and ultimately taxpayers—to TV stations. In addition, strategic supply reduction can potentially cause efficiency losses if it distorts the set of TV stations that relinquish their licenses in the reverse auction, and it can reduce the amount of spectrum that is re-purposed in the incentive auction.

Re-purposing spectrum from broadcast TV to mobile broadband usage is no doubt an extremely valuable and complex undertaking and the incentive auction was very carefully designed. The reverse auction takes the form of a deferred-acceptance clock auction. The theoretical development and analysis of the properties of this type of auction in Milgrom and Segal (2020) depends crucially on a so-called "single-mindedness" assumption. If, counterfactually, all TV stations were independently owned, then it would be a dominant strategy for each TV station to truthfully

[1] 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 Auction", 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.

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

bid its value as a broadcast business in the reverse auction; we refer to this as naive bidding.[3] The single-mindedness assumption thus does not accommodate owners internalizing the benefits of multi-license ownership.

Our paper points to unintended consequences of the multi-license ownership that is prevalent in the data. In particular, the rules of the reverse auction leave room for strategic supply reduction by multi-license owners. This behavior is purely rent-seeking, as these owners attempt to increase their share of existing wealth without creating any new wealth. Consistent with a supply reduction strategy, we document that the private equity firms sold 40% of the acquired TV stations in the reverse auction, off-loading another 54% of the acquired TV stations soon after. While the private equity firms made—typically substantial—profits on the TV stations they relinquished in the reverse auction, they incurred losses on the TV stations they sold soon after.

In a first step, we provide a model and a series of examples 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 TV stations are more suitable for a supply reduction strategy. We document that the private equity firms acquired TV stations that are broadly consistent with this implication.

In a second step, we quantify the payout increases caused by strategic supply reduction. To do so, we undertake a large-scale valuation exercise to estimate reservation values for all auction-eligible TV stations. We combine various data sources to estimate a TV station's cash flow and use it to infer the station's value as a going concern. With estimates in hand, we compare the initial outcome under naive bidding with the outcome under strategic bidding when we account for the ownership pattern in the data and allow multi-license owners to engage in strategic supply reduction. We enumerate all equilibria of a simplified version of the reverse auction that limits the geographic scope of strategic bidding and accounts for the repacking process at the regional—but not at the full national—level. We further assume that all auction-eligible TV stations participate in the reverse auction.

We show that strategic supply reduction has a large impact on prices and payouts to TV stations. For a clearing target of re-purposing 126 MHz of spectrum, the starting point of the incentive auction when it commenced on March 29, 2016, strategic bidding by multi-license owners increases nationwide payouts by 42.4%. For the 84 MHz clearing target that the incentive auction ultimately reached, strategic bidding increases nationwide payouts by 13.5%. These increases partly go to single-license owners, who as a group witness payout increases that are almost as large as those seen by multi-license owners.

We do not find a sizable distortion in the set of TV stations that relinquish their licenses in the reverse auction. Instead, the FCC purchases largely the same set of TV stations, but at higher

[3]Under the single-mindedness assumption, deferred-acceptance clock auctions have many other desirable properties. Milgrom and Segal (2020) show that they are not only strategy proof but also weakly group-strategy proof, meaning that no coalition of bidders has a joint deviation from truthful bidding that is strictly profitable for all members of the coalition. In addition, deferred-acceptance clock auctions are nearly optimal and, assuming complete information, equivalent to pay-as-bid auctions. Dütting, Gkatzelis and Roughgarden (2017) provide both positive and negative results on the fraction of total surplus that deferred-acceptance auctions can achieve.

prices. These payout increases reflect that strategic supply reduction changes the identity of the TV stations that, as they withdraw from the reverse auction, determine the prices for the TV stations that the FCC purchases. Hence, strategic supply reduction has limited efficiency implications in our setting. A particularly striking result of our simulation exercise is that the outcome of the reverse auction is sensitive to small changes in bidding behavior: withholding even a few TV stations suffices to give rise to equilibria that have significantly higher payouts than those under naive bidding. Reaching these equilibria may thus not require widespread coordination of expectations between multi-license owners.

Our paper may be viewed as measuring the importance of the single-mindedness assumption in Milgrom and Segal (2020) in a setting that is of immediate public policy concern. As such, our paper complements their theoretical analysis of the reverse auction. Beyond the reverse auction, the single-mindedness assumption plays an important role in the literatures on combinatorial auctions and algorithmic mechanism design in economics and computer science (Cramton, Shoham and Steinberg, 2010; Nisan et al., 2007).[4] More broadly, we provide a framework for evaluating the design of the reverse auction. Our paper differs from most of the empirical literature on auctions and market design, which typically takes an ex post perspective and uses realized outcomes combined with assumed equilibrium behavior to recover primitives such as preferences. In contrast, we take an ex ante perspective, similar to recent papers on online dating (Hitsch, Hortacsu and Ariely, 2010) and course allocation (Budish and Cantillon, 2012): we estimate reservation values from secondary, commercially available data and take them as an input into simulating the reverse auction.[5] We adopt an ex ante perspective in the hope that exercises similar to ours will prove 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 users in recent years.

We illustrate the potential usefulness of our framework in a number of ways. First, we propose a simple change in the auction rules and investigate the effect on payouts of placing a restriction on the bids of multi-license owners akin to an activity rule that eliminates the ability of multi-license owners to withdraw only those TV stations that, based on exogenous observed license attributes, are unlikely to garner large payouts in the reverse auction. We show that this rule change, by reducing the ability of multi-license owners to exploit the joint ownership of TV stations, mitigates the payout increase from strategic bidding by between 71% and 89%, depending on the clearing target.

Second, we investigate the consequences of a particular auction design choice that the FCC made. A key aspect to the incentive auction is a repacking process that sits between the reverse and the forward auctions. With it, the FCC reassigns all TV stations that opt to remain on the air post auction to new channels in order to clear a contiguous, nationwide block of spectrum

[4] The single-mindedness assumption was introduced by Lehmann, O'Callaghan and Shoham (2002) and motivated as being the simplest non-trivial (in the sense of computation) instance of a combinatorial auction.

[5] Even if more detailed data were available, the identification challenges discussed in Cantillon and Pesendorfer (2007) may make it difficult to extend the standard first-order conditions approach to our setting. The moment-inequalities approach in Fox and Bajari (2013) identifies relative valuations but not the levels that we require to quantify the effects of ownership concentration.

for mobile broadband usage. In the repacking process, TV stations are not homogeneous for geographic and technological reasons related to signal interference between nearby stations. The FCC's choice of allowable levels of interference between TV stations determines how easily TV stations can be substituted for one another. Our simulation exercise traces out the relationship between substitutability in the repacking process and payouts in the reverse auction. By exploring how substitutability affects the scope for strategic bidding, our paper adds a new dimension to previous studies of strategic supply reduction in multi-unit auctions with homogeneous products in wholesale electricity markets (e.g., Wolfram, 1998, Borenstein, Bushnell and Wolak, 2002, Hortacsu and Puller, 2008).

Finally, we use our framework to investigate the efficiency of the reverse auction. Extending previous work by Newman et al. (2017), we show that the reverse auction comes close to being efficient. While changes to the auction design can substantially reduce the transfer of wealth from the government to TV stations, the potential efficiency gains from re-designing the reverse auction therefore appear to be limited.

Our simulation exercise substantially underpredicts payouts in the actual reverse auction. We close the paper by tracing a large part of this gap back to two assumptions. First, we assume that all auction-eligible TV stations participate in the reverse auction in line with our ex ante perspective. Second, we limit the geographic scope of strategic bidding due to computational constraints. Relaxing these assumptions as much as possible, we show that they are conservative and that our main results are likely to understate the impact of strategic supply reduction on prices and payouts to TV stations.

By highlighting unintended consequences of ownership concentration for the reverse auction 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). Our paper builds on the theoretical literature on strategic bidding in multi-unit auctions (Wilson, 1979; Back and Zender, 1993, 2001; Engelbrecht-Wiggans and Kahn, 1998; Ausubel et al., 2014) that we come back to in Section 3 after illustrating how strategic supply reduction works in the reverse auction. It complements the experimental evidence for strategic demand reduction (List and Lucking-Reiley, 2000; Kagel and Levin, 2001; Engelmann and Grimm, 2009; Goeree, Offerman and Sloof, 2013) and case studies of past spectrum auctions (Weber, 1997; Cramton and Schwartz, 2002; Grimm, Riedel and Wolfstetter, 2003). Finally, our paper is 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). An important difference is that this literature focuses on collusion between independent bidders, whereas we focus on the strategic implications of multiple TV stations being held by the same owner.

The remainder of this paper is organized as follows: Section 2 provides background on the FCC incentive auction. Section 3 provides a model of the reverse auction and strategic supply reduction. Sections 4 and 5 present data and descriptive evidence in support of ownership concentration and strategic supply reduction. Sections 6 and 7 describe the main analysis of the reverse auction and results. Section 8 uses our framework to assess the design of the reverse auction and modifications to it. Section 9 presents extensions and argues that the assumptions underlying our analysis tend to be conservative. Section 10 concludes.

2 The FCC incentive auction

The rapid growth in data and video usage by smartphone users has significantly increased the demand for mobile broadband spectrum.[6] At the same time, some previously allocated spectrum is no longer used intensively. Each of approximately 7,900 currently operating TV stations in the U.S. holds a license to a 6 MHz block of spectrum in a particular geographical area dedicated to over-the-air transmission of programming.[7] Yet, as of 2010 only about 10% of TV households use broadcast TV, with a rapidly declining trend.[8]

In its 2010 National Broadband Plan, the FCC under then-chairman Julius Genachowski proposed, and received authorization by Congress in 2012, to conduct an incentive auction to reallocate spectrum from TV stations to wireless carriers. The incentive auction consists of a reverse auction, in which TV stations bid to relinquish their licenses in exchange for payment, and a forward auction, in which wireless carriers bid for the cleared spectrum. The reverse and forward auctions progress in a series of stages that are linked through a clearing target until a final stage rule terminates the incentive auction. The format of the incentive auction was publicly announced in June 2014.[9]

The FCC has used auctions to award licenses for the commercial use of spectrum since 1993, to exploit a market-based mechanism that relies on voluntary participation and is relatively robust to legal challenges.[10,11] In contrast to bilateral negotiations or take-it-or-leave-it offers, auctions are less time consuming and do not require the FCC to estimate participants' valuations of spectrum.

[6] According to FCC then-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 https://www.fcc.gov/news-events/blog/2014/02/11/channel-sharing-new-opportunity-broadcasters, accessed on November 15, 2015.

[7] As of March 31, 2016. See https://apps.fcc.gov/edocs_public/attachmatch/DOC-338754A1.pdf, accessed on March 28, 2018.

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

[9] See https://apps.fcc.gov/edocs_public/attachmatch/FCC-14-50A1.pdf, accessed on November 15, 2015.

[10] FCC then-chairman Tom Wheeler puts this as follows: "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 https://apps.fcc.gov/edocs_public/attachmatch/DOC-326215A1.pdf, accessed on November 15, 2015.

[11] Theoretically, the FCC could institute a mandatory hand-over of licenses, but TV stations would have a strong due process claim under the 5th Amendment's takings clause.

The incentive auction was the first time the FCC combined an auction to sell spectrum with an auction to buy spectrum from existing licensees.

Forward auction. The forward auction uses an ascending-clock format similar to previous spectrum auctions. The FCC accepted 62 qualified bidders into the forward auction. These wireless carriers bid for one or more licenses to contiguous blocks of spectrum in geographic areas called Partial Economic Areas (PEAs). There are 416 PEAs in the U.S.[12]

Reverse auction. The reverse auction uses a descending-clock format that we describe in detail in Section 3. The FCC declared 2,197 TV stations as eligible for the reverse auction, but revoked the licenses to three stations prior to the auction, reducing the number of auction-eligible stations to 2,194.[13] These TV stations are classified by type of service into UHF stations that broadcast between channel 14 and 36 or between channel 38 and 51 and VHF stations that broadcast between channel 2 and 13. They can be further classified by type of use into commercial and non-commercial stations and by power output into full-power stations (primary and satellite stations) and low-power class-A stations.[14] Appendix A.1 summarizes the types of TV stations.

A TV station has several options to relinquish its license: 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 (VHF channels 2-13 for UHF or low VHF channels 2-6 for high VHF) that is less desirable for wireless carriers, or sharing a channel with another TV station.[15] The auction rules stipulate that the payout to a VHF station for going off the air and the payouts to a UHF or a VHF station for moving bands are fixed fractions of the payout to a UHF station for going off the air; hence, the auction rules recognize the latter as the primary relinquishment option.

Its license entitles a TV station to broadcast a TV signal on a particular frequency from a particular location with a particular power output; the station cannot, on its own, choose to repurpose its license for a new use such as wireless service. The FCC assigns each TV station to a local media market called a designated market area (DMA). A DMA is defined by Nielsen Media Research based on the reach and viewing patterns of TV stations 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 A.2 lists the top ten DMAs based on their 2015 rank. The

[12] See https://apps.fcc.gov/edocs_public/attachmatch/DA-14-759A3.pdf and https://apps.fcc.gov/edocs_public/attachmatch/DA-14-759A4.pdf, accessed on August 3, 2017.

[13] See http://wireless.fcc.gov/auctions/incentive-auctions/Reverse_Auction_Opening_Prices_111215.xlsx, accessed on March 7, 2018. Prior to the reverse auction, the FCC revoked the licenses of UHF stations KLHU-CD (facility ID 30932) and DWKOG-LP (facility ID 34894) and VHF station WDHS (facility ID 15498). The FCC excludes approximately 5,500 low-power non-class-A and translator stations from the reverse auction.

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

[15] The FCC has piloted a channel-sharing arrangement in Los Angeles, CA, to show 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. However, 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. Hence, it is unclear how attractive this relinquishment option is.

210 DMAs do not map neatly into the 416 PEAs that are the relevant market area in the forward auction. For example, the New York, NY, DMA consists of 32 counties in 6 states (CT, NJ, NY, MA, PA, and RI) whereas the New York, NY, PEA consists of 42 counties in 4 states (CT, NJ, NY, and PA).

Because of this divergence in market areas and because the TV stations that opt to remain on the air may currently be located on any UHF or VHF channel, the FCC undertakes a repacking process in which it consolidates the remaining TV stations into the lower end of the UHF band and into the VHF band. This creates a contiguous block of spectrum for mobile broadband usage in the higher end of the UHF band in a process that is visually similar to defragmenting a hard drive on a personal computer. However, it is far more complex because many pairs of TV stations, even if located in different DMAs, cannot be assigned to the same or immediately adjacent channels without causing unacceptable levels of interference. Several factors influence interference, including geography and the height and power output of the broadcast tower. These interference constraints have two consequences. First, the repacking process ties together all DMAs and effectively takes place at the national level. Second, accommodating K remaining TV stations in a DMA typically requires far more than $6K$ MHz of spectrum. Throughout the remainder of the paper, we discuss how the auction design accommodates the interference constraints and highlight the role they play in the outcome of the reverse auction.

Clearing target and final stage rule. The auction rules integrate the reverse and forward auctions in a series of stages. The FCC sets an initial target for the amount of spectrum to clear and make available to wireless carriers. It then first runs the reverse auction to determine the payouts required to induce a set of TV stations to relinquish their licenses so that the clearing target can be met after repacking any TV stations that opt to remain on the air. Given the interference constraints on the repacking process, there are many different sets of TV stations that can relinquish their licenses to meet a particular clearing target; as a consequence, the FCC's "demand" for any particular TV station remains elastic.

The FCC next runs the forward auction to determine the willingness-to-pay of wireless carriers for the cleared spectrum. If the payouts demanded by TV stations in the reverse auction exceed the willingness-to-pay in the forward auction, then the FCC reduces the clearing target, requiring fewer TV stations to relinquish their licenses in the next stage of the incentive auction. The FCC repeats this process until proceeds in the forward auction more than cover payouts in the reverse auction and a final stage rule is met.[16]

Timeline and outcome. Technological and legal challenges resulted in several delays to the incentive auction from original projections for early 2014 to the ultimate starting date of March 29,

[16] Specifically, the final stage rule requires that proceeds in the forward auction are at least \$1.25 per MHz per population (henceforth, MHz-pop) for the largest 40 PEAs and not only cover payouts in the reverse auction, but also the reimbursements of channel relocation expenses incurred by TV stations in the repacking process, the FCC's administrative expenses for the incentive auction, and the funding of the First Responder Network Authority's public safety operations.

2016.[17] In line with our ex ante perspective, the first public version of this research paper appeared in April of 2016 while the auction was still ongoing.

The FCC set the initial clearing target to 126 MHz in stage 1 of the auction. TV stations demanded payouts of $86.4 billion in the reverse auction for relinquishing the licenses required to meet this clearing target, whereas wireless carriers offered only $23.1 billion for the cleared spectrum in the forward auction.

In stage 2, the FCC reduced the clearing target to 114 MHz, with bidding commencing on September 13, 2016. TV stations demanded $54.6 billion whereas wireless carriers offered $21.5 billion. In stage 3, the FCC reduced the clearing target to 108 MHz, with bidding commencing on November 1, 2016. TV stations demanded $40.3 billion whereas wireless carriers offered $19.7 billion.

In stage 4, the FCC reduced the clearing target to 84 MHz. Bidding in the reverse auction commenced on December 13, 2016 and bidding in the forward auction closed on March 30, 2017. The forward auction raised $19.6 billion in proceeds, covering payouts of $10.1 billion in the reverse auction and leaving proceeds of more than $7 billion for the U.S. Treasury. The fact that the FCC had to reduce the clearing target from 126 MHz to 84 MHz to trigger the final stage rule is widely attributed to unexpectedly weak demand for spectrum by wireless carriers in the forward auction.[18] The FCC concluded the process of reassigning channels to the TV stations that opted to remain on the air in the middle of 2020.[19]

In the forward auction, 50 out of 62 qualified bidders acquired a total of 2,776 licenses to mobile broadband spectrum. In the reverse auction, 175 out of 2,194 TV stations relinquished their licenses in some form: 141 UHF stations and 4 VHF stations went off the air and a further 29 UHF stations and 1 VHF station moved bands.[20] The FCC has released the identity of and payouts to these TV stations.[21] To protect the confidentiality of individual broadcasters, the FCC had initially decided not to release data on participation or bids in the reverse auction.[22] The FCC subsequently reversed this decision. We further report on the available data in Section 4.3.

3 A model of the reverse auction

We illustrate the potential for strategic supply reduction in a model of the reverse auction. The reverse auction is a deferred-acceptance clock auction. Our formalization of it draws on Appendix

[17]See 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", Edward Wyatt, The New York Times, October 24, 2014. See also http://www.shure.com/americas/incentive-auction-resource-center, accessed on March 7, 2018.

[18]See "FCC Airwaves Auction Cools for Broadcasters", Thomas Gryta and Joe Flint, The Wall Street Journal, January 19, 2017.

[19]See "FCC Announces Repack Complete, Spectrum Open for Wireless", Michael Balderston, TV Tech, July 13, 2020.

[20]See https://auctiondata.fcc.gov/public/projects/1000, accessed on March 7, 2018.

[21]See https://auctiondata.fcc.gov/public/projects/1000/reports/reverse-winning_bids, accessed on March 7, 2018.

[22]See https://docs.fcc.gov/public/attachments/FCC-15-78A1.pdf, accessed on March 7, 2018.

D of FCC Public Notice 14-191 and Milgrom and Segal (2020).[23,24] We leverage that the auction design limits interactions between the reverse and forward auctions and take the clearing target as given in our analysis. We follow Milgrom and Segal (2020) and focus on going off the air as the primary relinquishment option; as shown in Kazumori (2016), modeling channel sharing or band switching is a nontrivial undertaking.

There are N stations that participate in the reverse auction. Let $v_j > 0$ denote the reservation value of TV station j that captures its value as a going concern. The reverse auction progresses in rounds. Let $P_\tau \geq 0$ denote the base clock price in round τ. The base clock price decreases over the course of the reverse auction and maps into a "personalized" price $\varphi_j P_\tau$ for TV station j through its broadcast volume, defined as

$$\varphi_j = M\sqrt{InterferenceFreePop_j \cdot InterferenceCount_j}. \tag{1}$$

The FCC uses the broadcast volume to incentivize those TV stations to relinquish their licenses that are particularly valuable as broadcast businesses or particularly difficult to assign channels if they opt to remain on the air. The former is proxied for by the interference free population $InterferenceFreePop_j$, a measure of the population served by TV station j. The latter is proxied for by the interference count $InterferenceCount_j$ that is derived from the number of interference constraints involving TV station j that the repacking process has to respect.[25] Finally, the FCC sets the scale factor $M = 17.253$ so that $\max_{j\in\{1,\dots,N\}} \varphi_j = 1,000,000$.

Given its personalized price $\varphi_j P_\tau$ in round τ, TV station j may withdraw from the reverse auction and require a channel assignment to remain on the air. The FCC, by law, has to be able to assign a channel to any TV station that withdraws from the reverse auction at any point. The auction design integrates a piece of software, the feasibility checker $SATFC$ (Frechette, Newman and Leyton-Brown, 2016), to ensure this is always the case. The feasibility checker $SATFC$ defines an indicator function $S(X, R)$ that equals one if a set of TV stations $X \subseteq \{1, \dots, N\}$ can be repacked into a set of available channels R and zero otherwise.[26] To simplify the notation, we suppress that $S(X, R)$ depends on a set of interference constraints that codifies the pairs of TV stations that cannot be located on the same or immediately adjacent channels. We further suppress that R depends on the given clearing target; intuitively, R is smaller for a larger clearing target.

The reverse auction defines an extensive-form game. In round $\tau \geq 1$, the set of TV stations $\{1, \dots, N\}$ is partitioned into a set of "active" TV stations A_τ that may withdraw from the reverse auction, a set of "inactive" TV stations I_τ that have already withdrawn, and a set of "frozen" (or "conditionally winning") TV stations F_τ. By withdrawing, an active TV station may freeze one

[23]See https://apps.fcc.gov/edocs_public/attachmatch/FCC-14-191A1.pdf, accessed on March 10, 2016.

[24]See Bikhchandani et al. (2011) for earlier work on deferred-acceptance auctions. Bikhchandani et al. (2011), in turn, build on the idea in Ausubel (2004; 2006) of making partial, irrevocable allocations as the auction progresses.

[25]See Section 2.2 of Appendix D of FCC Public Notice 14-191 and footnote 2 of http://wireless.fcc.gov/auctions/incentive-auctions/Reverse_Auction_Opening_Prices_111215.xlsx, accessed on March 7, 2018.

[26]The feasibility checker $SATFC$ returns SAT to indicate that the set of TV stations X can be repacked into the set of available channels R, $UNSAT$ to indicates that it cannot, and $TIMEOUT$ to indicate that it has not succeeded in ascertaining feasibility in a pre-allotted amount of time. The FCC interprets $TIMEOUT$ as $UNSAT$.

or more other active TV stations if the FCC can no longer guarantee a channel assignment for these stations. Hence, as the reverse auction progresses and the base clock price decreases from round τ to round $\tau + 1$, active TV stations become either inactive or to frozen so that $A_{\tau+1} \subseteq A_\tau$, $I_{\tau+1} \supseteq I_\tau$, and $F_{\tau+1} \supseteq F_\tau$.

In round 1, the base clock price is initialized as $P_1 = 900$ and all TV stations as active, i.e., $A_1 = \{1, \ldots, N\}$, $I_1 = \emptyset$, and $F_1 = \emptyset$. In round $\tau \geq 1$, given its personalized price $\varphi_j P_\tau$, active TV station $j \in A_\tau$ may withdraw from the reverse auction and collect the payout $PO_j = 0$. Let Y_τ be the set of active TV stations that withdraw from the reverse auction in round τ. In round $\tau + 1$, the set of inactive TV stations is thus $I_{\tau+1} = I_\tau \cup Y_\tau$; these are all TV stations that have previously withdrawn and require channel assignments. For ease of exposition, we assume that at most one active TV station withdraws in round $\tau > 1$ but allow any number of stations to withdraw in round 1.[27,28] The FCC then checks if it can guarantee a channel for each remaining active TV station $j' \in A_\tau \setminus Y_\tau$ in round $\tau + 1$. If, as a consequence of TV station j withdrawing, the FCC cannot guarantee a channel for TV station j', then that TV station is frozen and collects the payout $PO_{j'} = \varphi_{j'} P_\tau$ in return for relinquishing its license. Let $Z_\tau = \{j' \in A_\tau \setminus Y_\tau | S(I_{\tau+1} \cup \{j'\}, R) = 0\}$ be the set of active TV stations that are newly frozen in round τ because they cannot be repacked in addition to the TV stations that have previously withdrawn.

The next round $\tau + 1$ sets a lower base clock price $P_{\tau+1}$ and updates the set of frozen stations to $F_{\tau+1} = F_\tau \cup Z_\tau$ and the set of active stations to $A_{\tau+1} = A_\tau \setminus (Y_\tau \cup Z_\tau)$. The reverse auction continues in this way as long as an active TV station remains and the base clock price is above its lower bound of zero. If $A_{\tau+1} = \emptyset$ or $P_{\tau+1} = 0$, then the reverse auction concludes after round τ.[29]

To complete the description of the extensive-form game, we specify the information sets of the TV stations. The FCC computes and publishes the broadcast volume of all TV stations before the start of the reverse auction. During the course of the reverse auction, the FCC releases minimal information to and forbids communication between TV stations.[30] Because a TV station observes solely its personalized price but not the decisions of other TV stations, we assume that a strategy for a TV station simply specifies a critical value for the base clock price above which the TV station continues in the reverse auction and at or below which the TV station opts to remain on the air.[31]

[27] In practice, the FCC uses a random tie-breaking rule that entails our assumption that at most one active TV station withdraws in round $\tau > 1$ (FCC Public Notice 15-78, p. 63).

[28] If in round 1 the TV stations that withdraw from the reverse auction cannot be repacked, then the reverse auction fails at the outset and the payouts to all TV stations are zero.

[29] At the conclusion of the reverse auction, we assume that any remaining active TV station $j \in A_{\tau+1}$ is frozen at the base clock price $P_{\tau+1} = 0$.

[30] To be precise, in round τ of the reverse auction the FCC shows TV station j its personalized price $\varphi_j P_\tau$ and which of the three intervals $[0.5, 3)$, $[3, 6]$, or $(6, |R|]$ its vacancy index belongs to. The vacancy index of TV station j in round τ is defined as

$$VI_{j\tau} = \frac{\sum_{k \in G_{j\tau}} \varphi_k \max\{0.5, H_{k\tau}\}/|R|}{\sum_{k \in G_{j\tau}} \varphi_k},$$

where $H_{k\tau}$ is the total number of feasible channels for TV station k in round τ and $G_{j\tau}$ is the set of TV stations that have not been repacked in round τ but interfere with TV station j.

[31] In doing so, we follow a long tradition in the auction literature of omitting the possibility that the participants learn something during the course of an auction that may cause them to revise their critical values (Milgrom, 2004, p. 187).

Table 1: Example 1: Strategic supply reduction and overbidding

Station ID (j)	Firm ID	Reservation value (v_j)	Broadcast volume (φ_j)	Score ($s_j = \frac{v_j}{\varphi_j}$)
2	2	500	1	500
3	1	300	1	300
1	1	100	1	100

In the subsequent analysis we refer to this critical value as the "bid" $b_j \geq 0$ of TV station j.

Depending on whether a TV station knows the reservation values of other TV stations or not, the game is one of complete or incomplete information. We distinguish these cases in our subsequent analysis as needed, but do not assume that the FCC knows the reservation values of the TV stations in either case.

3.1 Strategic supply reduction, overbidding, and underbidding

In analyzing deferred-acceptance clock auctions, Milgrom and Segal (2020) assume that bidders are "single-minded." This, in particular, requires that a bidder has a single object for sale. Under this single-mindedness assumption, it is easy to see that truthful bidding is a dominant strategy in the sense of Li (2017) or "always optimal" in the sense of Milgrom (2004, p. 50), irrespective of whether the game is one of complete or incomplete information. In the context of the reverse auction, this means that an independently owned TV station withdraws from the reverse auction once its personalized price $\varphi_j P_\tau$ falls to its value as a going concern v_j, or $\varphi_j P_\tau = v_j$. We henceforth refer to this strategy of bidding $b_j = \frac{v_j}{\varphi_j}$ as naive bidding and to $s_j = \frac{v_j}{\varphi_j}$ as the "score" of TV station j.

We use a series of examples to illustrate two points. First, we show that a firm owning multiple TV stations may have an incentive to deviate from naive bidding. Hence, naive bidding may no longer be an equilibrium if TV stations are jointly owned. Second, we illustrate the potential for multiple equilibria, not just in settings where bidders are single-minded, but also in settings with jointly owned TV stations. We begin with a first example that results in strategic supply reduction and overbidding $b_j > s_j$, before turning to a second example that illustrates underbidding $b_j < s_j$. For simplicity, we proceed in a game of complete information.

Example 1: Strategic supply reduction and overbidding. There are $N = 3$ TV stations with the reservation values and broadcast volumes given in Table 1. TV stations 1 and 3 are owned by firm 1 and TV station 2 is owned by firm 2. The set of available channels R and the interference constraints are such that the FCC can repack just one of the three TV stations, i.e.,

$$S(X, R) = \begin{cases} 1 & \text{if} \quad X = \emptyset, \{1\}, \{2\}, \{3\}, \\ 0 & \text{if} \quad X = \{1,2\}, \{1,3\}, \{2,3\}, \{1,2,3\}. \end{cases} \tag{2}$$

Under naive bidding, $b_j = s_j$ for all $j \in \{1, 2, 3\}$ and TV station 2 is first to withdraw from the reverse auction at a base clock price of $P_\tau = 500$. As a consequence of TV station 2 requiring a channel assignment to remain on the air, TV stations 1 and 3 can no longer be repacked and are frozen, collecting payouts $PO_1 = PO_3 = 500$. The reverse auction concludes and firm 1's profit from the reverse auction is $500 - 100 + 500 - 300 = 600$. Firm 2's profit is 0 as TV station 2 remains a going concern.

However, naive bidding is not an equilibrium as firm 1 has an incentive to deviate. In particular, if instead $b_1 = s_1$ and $b_3 = 900$, then firm 1 effectively withholds TV station 3 from the reverse auction at the initial base clock price of $P_1 = 900$. As a consequence, TV stations 1 and 2 can no longer be repacked and are frozen, collecting payouts $PO_1 = PO_2 = 900$. The reverse auction concludes and firm 1's profit from the reverse auction is $900 - 100 = 800$. By strategically reducing supply, firm 1's profit increases from 600 to 800. Firm 2's profit also increases from 0 to $900 - 500 = 400$. Indeed, it is easy to see that $b_1 = s_1$, $b_2 = s_2$, and $b_3 = 900$ is an equilibrium. Note that in this equilibrium two TV stations relinquish their licenses, just as under naive bidding. Yet, strategic supply reduction increases payouts to TV stations from $1,000$ to $1,800$. Further note that truthful bidding remains a dominant strategy for firm 2 even though firm 1 engages in strategic supply reduction by withholding one of its TV stations from the reverse auction.[32]

The literature has widely recognized the potential for strategic supply reduction in buying instead of selling auctions involving multiple objects, starting with Wilson (1979). Back and Zender (1993; 2001) and Engelbrecht-Wiggans and Kahn (1998) subsequently establish strategic demand reduction in static auctions. In dynamic auctions, strategic demand reduction is shown in Menezes (1996), Brusco and Lopomo (2002), Engelbrecht-Wiggans and Kahn (2005), and Riedel and Wolfstetter (2006). This literature culminates in Ausubel et al. (2014), who under fairly general conditions show strategic demand reduction in static auctions, and whose arguments largely extend to dynamic auctions. Our setting differs from this earlier literature that focused on homogeneous products in that the interference constraints on the repacking process effectively render TV stations differentiated products. We revisit this point in Section 8.2.

A generalization of this example illustrates when strategic supply reduction is profitable for a firm owning multiple TV stations. Consider arbitrary reservation values and broadcast volumes such that $\max\{s_1, s_3\} < s_2 < 900$, where $s_j = \frac{v_j}{\varphi_j}$ is the score of TV station j. Note that TV stations 1 and 3 continue to be frozen at a base clock price of s_2 under naive bidding. Firm 1's profit under naive bidding is $s_2(\varphi_1 + \varphi_3) - (v_1 + v_3)$ whereas its profit from withholding TV station 3 from the reverse auction now is $900\varphi_1 - v_1$. Strategic supply reduction is more profitable than

[32]To show that the profit $\pi_j(b_j, b_{-j})$ of an independently owned TV station j under the truthful bid $b_j = s_j$ is at least as large as that under any alternative bid $\tilde{b}_j \neq s_j$ irrespective of the vector b_{-j} of bids of the other TV stations, we proceed case by case. Suppose first that bids (s_j, b_{-j}) leave TV station j on the air so that $\pi_j(s_j, b_{-j}) = 0$. Then any $\tilde{b}_j < s_j$ either continues to yield $\pi_j(\tilde{b}_j, b_{-j}) = 0$ or freezes TV station j at a base clock price below s_j, yielding $\pi_j(\tilde{b}_j, b_{-j}) < 0$. Moreover, any $\tilde{b}_j > s_j$ continues to yield $\pi_j(\tilde{b}_j, b_{-j}) = 0$. Next suppose that bids (s_j, b_{-j}) freeze TV station j so that $\pi_j(s_j, b_{-j}) > 0$. Then any $\tilde{b}_j < s_j$ freezes TV station j at the same base clock price as s_j and thus continues to yield $\pi_j(\tilde{b}_j, b_{-j}) = \pi_j(s_j, b_{-j})$. Moreover, any $\tilde{b}_j > s_j$ either freezes TV station j at the same base clock price as s_j and thus continues to yield $\pi_j(\tilde{b}_j, b_{-j}) = \pi_j(s_j, b_{-j})$ or leaves TV station j on the air, yielding $\pi_j(\tilde{b}_j, b_{-j}) = 0$.

Table 2: **Example 2: Underbidding**

Station ID (j)	Firm ID	Reservation value (v_j)	Broadcast volume (φ_j)	Score ($s_j = \frac{v_j}{\varphi_j}$)
3	1	100	$\frac{1}{3}$	300
2	2	1000	5	200
1	1	100	1	100

naive bidding if

$$(900 - s_2)\varphi_1 > s_2\varphi_3 - v_3.$$

On the right-hand side is the forgone profit from withholding TV station 3. On the left-hand side is the additional profit consisting of the increase in the base clock price from s_2 to 900, "magnified" by the broadcast volume of TV station 1. Withholding TV station 3 is thus more likely to be profitable if it has a low broadcast volume and a high reservation value and TV station 1 has a high broadcast volume. Furthermore, it is more profitable for firm 1 to withhold TV station 3 rather than TV station 1 from the reverse auction if

$$900(\varphi_1 - \varphi_3) > v_1 - v_3.$$

This again is more likely to be satisfied if TV station 3 has a low broadcast volume and a high reservation value and TV station 1 has a high broadcast volume and a low reservation value. In short, strategic supply reduction is more likely to be profitable if the "leverage" from increasing the base clock price is large and the opportunity cost of continuing to operate the withheld TV station is small.

Example 2: Underbidding. Our next example shows that a firm owning multiple TV stations may also engage in underbidding. There are $N = 3$ TV stations with reservation values and broadcast volumes given in Table 2. We now allow the broadcast volume to vary across stations; consequently, the payout to a TV station is the base clock price at the time of its freeze scaled by its broadcast volume. As in Example 1, TV stations 1 and 3 are owned by firm 1 and TV station 2 is owned by firm 2. The set R of available channels and the interference constraints are now such that the FCC can repack either just one of the TV stations or TV stations 1 and 3 together, i.e.,

$$S(X,R) = \begin{cases} 1 & \text{if} \quad X = \emptyset, \{1\}, \{2\}, \{3\}, \{1,3\}, \\ 0 & \text{if} \quad X = \{1,2\}, \{2,3\}, \{1,2,3\}. \end{cases} \tag{3}$$

Under naive bidding, $b_j = s_j$ for all $j \in \{1,2,3\}$. TV station 3 is first to withdraw from the reverse auction at a base clock price of $P_\tau = 300$. As a consequence, TV station 2 can no longer be repacked and is frozen, collecting payout $PO_2 = 5 \cdot 300 = 1500$. TV station 1 is next to withdraw at a base clock price of $P_{\tau'} = 100$. The reverse auction concludes and firm 1's profit is 0 as TV stations 1 and 3 remain going concerns. Firm 2's profit is $1500 - 1000 = 500$.

However, naive bidding is no longer an equilibrium as firm 1 has an incentive to deviate. In particular, if instead $b_1 = s_1$ and $b_3 = 0$, then TV station 2 is first to withdraw from the reverse auction at a base clock price of $P_\tau = 200$. As a consequence, TV stations 1 and 3 can no longer be repacked and are frozen, collecting payouts $PO_1 = 200$ and $PO_3 = \frac{200}{3}$. The reverse auction concludes and firm 1's profit is $200 - 100 + \frac{200}{3} - 100 = \frac{200}{3}$. It is easy to see that $b_1 = s_1$, $b_2 = s_2$, and $b_3 = 0$ is an equilibrium. By underbidding, firm 1's profit increases from 0 to $\frac{200}{3}$. In contrast, firm 2's profit decreases from 500 to 0.

Multiple equilibria. In illustrating the potential for multiple equilibria, we contrast the single-mindedness assumption of Milgrom and Segal (2020) that rules out jointly owned TV stations, with the case of jointly owned TV stations as we observe in the data. For brevity, we focus on Example 1. In Online Appendix A.5, we show that there also are multiple equilibria in Example 2.

If we impose the single-mindedness assumption on Example 1 as though all TV stations were independently owned, then the set of equilibria is

$$\begin{aligned}
&\left\{(b_1, b_2, b_3) \in [0,\infty)^3 | b_1 \geq 500, b_2 \leq 100, b_3 \leq 100\right\} \\
&\cup \left\{(b_1, b_2, b_3) \in [0,\infty)^3 | b_1 \leq 300, b_2 \leq 300, b_3 \geq 500\right\} \\
&\cup \left\{(b_1, b_2, b_3) \in [0,\infty)^3 | \max\{b_1, b_3\} < b_2, 300 \leq b_2 \leq 500\right\} \\
&\cup \left\{(b_1, b_2, b_3) \in [0,\infty)^3 | \max\{b_1, b_3\} \leq 500, b_2 > 500\right\} \\
&\cup \left\{(b_1, b_2, b_3) \in [0,\infty)^3 | b_1 \geq 900, b_2 \geq 900, b_3 \geq 900\right\}.
\end{aligned} \tag{4}$$

The auction rules thus admit a wide range of behaviors and outcomes, although a range of behaviors may result in identical outcomes in terms of payouts to each license.[33] Focusing on truthful bidding as a dominant strategy amounts to singling out a particular equilibrium.

Recognizing that TV stations 1 and 3 are jointly owned, the set of equilibria in Example 1 is

$$\begin{aligned}
&\left\{(b_1, b_2, b_3) \in [0,\infty)^3 | b_1 < 900, b_2 \leq 600, b_3 \geq 900\right\} \\
&\cup \left\{(b_1, b_2, b_3) \in [0,\infty)^3 | b_1 \leq 500, b_2 \geq 600, b_3 \leq 500\right\}.
\end{aligned} \tag{5}$$

The fact that truthful bidding is no longer an equilibrium complicates analyzing the reverse auction. While focusing on truthful bidding as a dominant strategy for the independently owned TV station 2 shrinks the set of equilibria, it does not lead to a unique equilibrium. At the same time, the auction rules admit a rich set of behaviors by firms owning multiple TV stations, most notably

[33] The equilibria in the first four lines of equation (4), as well as those in the second line of equation (5), have the property that the TV station with the high bid is indifferent across a range of bids although its bid determines the payouts to the other TV stations. In this regard, these equilibria are reminiscent of the analysis of the combinatorial clock auction in Levin and Skrzypacz (2016). The combinatorial clock auction has been used to award spectrum in other countries. It combines an initial ascending clock phase during which participants state their demands in response to the current price with a final sealed package bidding phase and links the two phases by activity rules. In our model there is no analog to the predatory equilibria in Levin and Skrzypacz (2016) as these rely on the two-stage nature of the combinatorial clock auction.

including strategic supply reduction. Strategic supply reduction is an extreme form of overbidding in that a firm owning multiple TV stations withholds one or more of them from the reverse auction. There are other equilibria that entail milder forms of overbidding.

Given the large number of participating TV stations and the complex ownership patterns and interference constraints in the actual reverse auction, our subsequent analysis proceeds with a game of complete information and restricts the strategy space of firms owning multiple TV stations. Section 3.2 motivates these restrictions.

3.2 Further analysis

We follow Milgrom and Segal (2020) by focusing on truthful bidding as a dominant strategy for an independently owned TV station. We restrict the strategy space for a jointly owned TV station to extreme overbidding, extreme underbidding, and truthful bidding. The strategy space of TV station j is thus $b_j = s_j$ if it is independently owned and $b_j \in \{0, s_j, 900\}$ if it is jointly owned. We argue below that this restriction on jointly owned TV stations is not overly arduous.

We partition the vector $b = (b_1, \ldots, b_N)$ as (b_j, b_{-j}), where b_j is the bid for TV station j and b_{-j} is the vector of bids of the other TV stations. In the interest of simplicity, we assume that different TV stations have different bids, i.e., $b_j \neq b_k$ for all $j \neq k$, except that we allow multiple TV stations to bid 0 or 900. Let $\pi_i(b)$ be firm i's profit from the reverse auction. Denoting as $J_i \subseteq \{1, \ldots, N\}$ the set of TV stations owned by firm i and as $F^* \subseteq \{1, ..., N\}$ the set of frozen TV stations at the conclusion of the reverse auction, we have

$$\pi_i(b) = \sum_{j \in J_i \cap F^*(b)} PO_j(b) - v_j,$$

where our notation emphasizes that the payout PO_j to TV station j as well as the set of frozen TV stations F^* depend on the vector of bids b.

We motivate the restriction to $b_j \in \{0, s_j, 900\}$ for a jointly owned TV station j with two propositions. Proposition 1 tackles the case of overbidding:

Proposition 1. *Suppose firm i owns multiple TV stations including TV station j, i.e., $|J_i| > 1$ and $j \in J_i$. Consider a vector of bids b with $s_j < b_j < 900$. If $S(Y_1(b) \cup \{j\}, R) = 1$ and $\pi_i(b_j, b_{-j}) > \pi_i(s_j, b_{-j})$, then $\pi_i(900, b_{-j}) \geq \pi_i(b_j, b_{-j})$.*

Proposition 1 assumes that it is feasible to repack TV station j in addition to any TV stations that withdraw in round 1 of the reverse auction. It states that if a firm owning multiple TV stations finds it more profitable to overbid $b_j > s_j$ than to truthfully bid $b_j = s_j$, then the firm may as well bid $b_j = 900$ and withhold TV station j from the reverse auction. In this sense, restricting the strategy space of the jointly owned TV station j from $b_j \in [s_j, 900]$ to $b_j \in \{s_j, 900\}$ does not make the firm worse off. Moreover, it is easy to construct specific situations where extreme overbidding $b_j = 900$ ensures a strictly higher profit.

Proposition 1 is best thought of as characterizing the best reply of firm i and differs from the standard notion of weak dominance. While eliminating strictly (but not weakly) dominated strategies is innocuous and does not affect the set of equilibria, the restriction to $b_j \in \{0, s_j, 900\}$ for a jointly owned TV station j may well do so (see the examples in Section 3.1). Alas, a stronger result than Proposition 1 has eluded us. We note that the notion of dominance in Milgrom and Segal (2020) is also weaker than strict dominance.

Proposition 2 tackles the case of underbidding and parallels Proposition 1. We formally state it in Appendix B, where we also prove Propositions 1 and 2.

While our subsequent analysis proceeds with a game of complete information, our notion of strategic supply reduction in settings with jointly owned TV stations extends beyond complete information. It is well known that analyzing auctions involving multiple objects under the assumption of incomplete information is difficult (see Chapters 5 and 6 of Milgrom (2004) and Part II, especially Chapter 18, of Krishna (2010)). To make some headway, we recast Example 1 in Section 3.1 as a game of incomplete information in Online Appendix B.

In sum, while strategic supply reduction is part and parcel of the reverse auction, even our simple examples point to multiple equilibria and behavior within equilibria that depends critically on reservation values, broadcast volumes, and interference constraints. It is therefore difficult to arrive at general predictions about the outcome of the reverse auction and how that outcome differs between strategic bidding under the actual ownership pattern and truthful bidding under the counterfactual of independent ownership. In the subsequent analysis, we therefore combine estimated reservation values with simulation techniques to assess the impact of ownership concentration on the reverse auction.

4 Data sources

We first describe the various data sources we combine to estimate the reservation values of the TV stations participating in the reverse auction and to determine their ownership structure. Then we turn to the interference constraints on the repacking process. Finally, we describe some auxiliary data sources. We provide further details on the data sources in Appendix A.

From hereon, we restrict attention to TV stations located in the U.S. excluding Puerto Rico and the Virgin Islands. Out of the 2,194 TV stations that the FCC has declared as eligible for the reverse auction, 44 are located in Puerto Rico and the Virgin Islands.[34] This leaves us with 2,150 auction-eligible TV stations.

4.1 Reservation values and ownership structure

To infer the reservation value of a TV station in the reverse auction, we use the MEDIA Access Pro Database from 2003 to 2013 and for 2015 from BIA Kelsey (henceforth BIA) and the Television

[34]Out of the 145 TV stations that went off the air, 7 are located in Puerto Rico. These 7 TV stations together claimed less than 0.5% of payouts in the reverse auction.

Financial Report from 2003 to 2012 from the National Association of Broadcasters (NAB). We model and estimate the components of the cash flow of a TV station, focusing on advertising and non-broadcast revenue and fixed cost, as detailed in Section 6.1. BIA contains the universe of TV stations. It provides station, owner, and market characteristics, as well as transaction histories covering the eight most recent changes in the ownership of a TV station.

The revenue measure in the BIA data covers revenue related to broadcasting in the form of local, regional, and national advertising revenue, commissions, and network compensation, and we refer to it as advertising revenue in what follows. For commercial full-power and class-A stations, advertising revenue is missing for 24.9% of station-year observations, and we impute it as detailed in Appendix A.3. For non-commercial stations, including dark stations, advertising revenue is missing for 99.2% of station-year observations, and we do not impute it. We return to the distinction between commercial and non-commercial stations in Section 6.1.

The BIA data excludes non-broadcast revenue, most notably retransmission fees that TV stations charge pay-TV providers to use their content. Retransmission fees are a small but growing source of revenue.[35] Outside estimates suggest that in 2016 advertising revenue accounts for 69% of a typical TV station's revenue, with a further 24% of revenue coming from retransmission fees and 7% coming from online activities.[36] Consequently, the variation in advertising revenue across TV stations is a major, but not the only, driver of the variation in cash flow.

To get at non-broadcast revenue, we use the NAB 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 non-broadcast revenue. Expenses are similarly broken down into categories from which we are able to construct fixed cost. NAB further covers cash flow. However, for confidentiality reasons, NAB reports only the mean as well as the first, second, and third quartile of these measures at various levels of aggregation, resulting in "tables" of station groupings 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 A.4 lists the set of 66 tables for 2012; other years are very similar. In Section 6.1, we describe a method for combining the station-level data on advertising revenue from BIA with the aggregated data from NAB to estimate the cash flow of a TV station.

4.2 Interference constraints

The FCC makes available the feasibility checker $SATFC$ it uses in the reverse auction along with a domain file and a pairwise interference file.[37] The domain file lists for each TV station the channels it can be assigned to, accounting for restrictions due to international and military broadcasting. Intersecting the domain file with the channels that a given clearing target leaves available for

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

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

[37] See http://data.fcc.gov/download/incentive-auctions/Constraint_Files/, accessed on March 7, 2018.

repacking yields the set of available channels R described in Section 3.[38]

The pairwise interference file lists for each TV station and each channel any other TV stations that cannot be located on that channel or on immediately adjacent channels without causing unacceptable levels of interference; these are the interference constraints described in Section 3 that we suppress in our notation for the indicator function $S(X, R)$ for simplicity. In authorizing the Incentive Auction, Congress instructed the FCC to preserve the TV stations' populations served prior to the auction. After public deliberations on the interpretation of this mandate,[39] the FCC applied an existing standard that treats interference of more than 0.5% as unacceptable. Accordingly, a channel assignment for a pair of TV stations j and j' is included in the pairwise interference file and thus unavailable in the repacking process if transmission by TV station j would reduce the population served of TV station j' by more than 0.5%.[40] For most of the subsequent analysis, we rely on the pairwise interference file for the chosen 0.5% standard. We also trace out how the ease of repacking as parameterized by the interference level affects the outcome of the reverse auction. In Section 8.2 we rely on the pairwise interference files for an alternative, looser, standard of 2% that the FCC considered and for a very relaxed 10% standard.

Under a 126 MHz clearing target with UHF channels 14-29 available for repacking, the pairwise interference file imposes 1,626,176 restrictions on the repacking process for an interference level of 0.5%; under an 84 MHz clearing target with UHF channels 14-36 available for repacking, the number of restrictions grows to 2,334,334. To illustrate, Figure 1 shows the 87 TV stations that have interference constraints with WCAU (facility ID 63153), the Philadelphia NBC affiliate, on at least one of the 16 available channels under the 126 MHz clearing target. All TV stations have same-channel constraints and 27 of the 87 TV stations have adjacent-channel constraints. In Figure 1, the green dot indicates WCAU, a yellow dot a TV station with a same-channel constraint, and a red dot a TV station with an adjacent-channel constraint.

4.3 Auxiliary data sources

As described in "Appendix: Analysis of Potential Aggregate Interference" of FCC Public Notice DA 14-677, the FCC conducted its own simulations in June 2014 to assess the likely number of TV stations in each DMA that have to relinquish their licenses for a clearing target of 84 MHz or 120 MHz to be met.[41] The FCC restricts its simulations to UHF stations and to going off the air as the primary relinquishment option. Focusing on the simulations that assume full participation leaves us with 25 simulations for the 84 MHz clearing target and 27 simulations for the 120 MHz

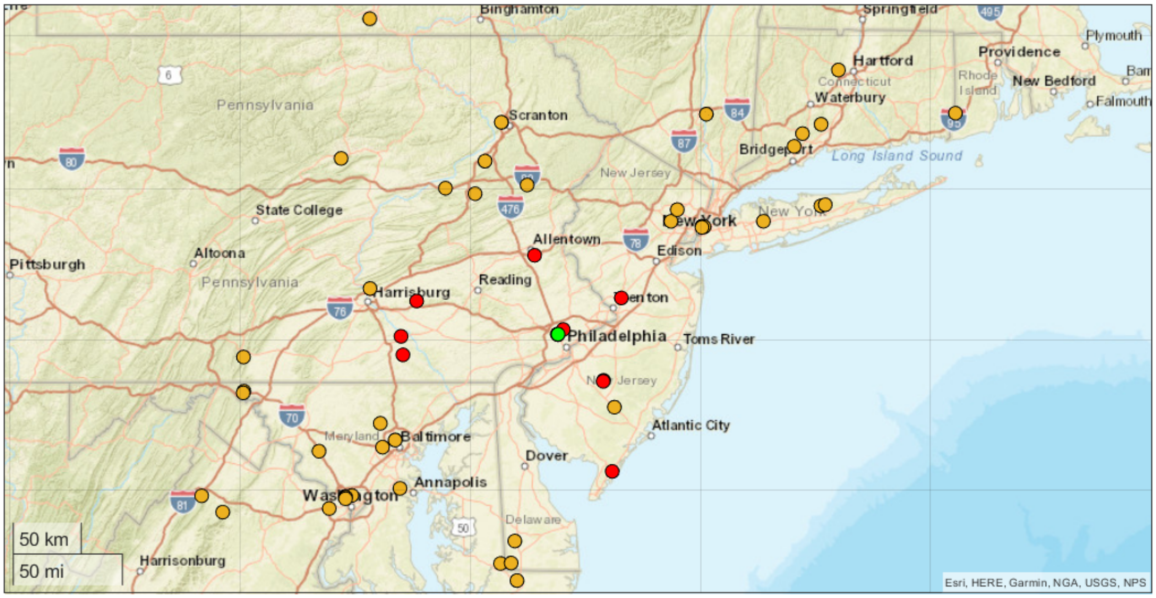
[38] For example, achieving the initial clearing target of 126 MHz requires clearing 21 out of a total of 37 non-dedicated UHF channels, leaving 16 UHF channels available for repacking; achieving the final clearing target of 84 MHz requires clearing 14 UHF channels, leaving 23 UHF channels available for repacking (FCC Public Notice 14-191, p. 7).

[39] See https://apps.fcc.gov/edocs_public/attachmatch/FCC-14-50A1.pdf, paragraphs 176-182, accessed on November 15, 2015.

[40] The FCC developed a piece of software, *TV Study*, that relies on geographically fine interference data to generate the pairwise interference file for any given interference level. See https://www.fcc.gov/oet/tvstudy, accessed on March 7, 2018.

[41] See https://apps.fcc.gov/edocs_public/attachmatch/DA-14-677A2.docx, accessed on March 10, 2016.

Figure 1: Same- and adjacent-channel interference constraints for WCAU



Notes: Dots denote facility locations. The green dot denotes WCAU. Red dots denote TV stations that have adjacent-channel interference constraints with WCAU and yellow dots TV stations that have same-channel interference constraints.

clearing target. For our initial descriptive analysis only, we label a DMA as a positive demand DMA if at the median across simulations at least one TV station has to relinquish its license. In many DMAs no TV station has to relinquish its license for the clearing target to be met; hence, we expect payouts from the reverse auction to be concentrated in a relatively small number of DMAs.

While the FCC had initially decided not to release data on participation or bids in the reverse auction and Milgrom and Segal (2020) maintain that "by law, bids in the auction cannot be revealed" (p. 27), the FCC recently released data that records the price at which a participating TV station withdrew from the reverse auction.[42] We use this data to validate our estimated reservation values in Section 6.1 and to assess the sensitivity of the reverse auction to reduced participation in Section 9.1.

5 Descriptive evidence

We provide descriptive evidence in support of ownership concentration and strategic supply reduction. From here on, in line with the FCC's own simulations we restrict attention to the 1,670 UHF stations located in the U.S. excluding Puerto Rico and the Virgin Islands that the FCC has declared as eligible for the reverse auction.[43] The 1,670 TV stations are assigned to 202 DMAs by

[42]See https://auctiondata.fcc.gov/public/projects/1000/reports/reverse-bids, accessed on February 15, 2022.

[43]We drop 480 VHF stations from the subsequent analysis. These 480 VHF stations together claimed a mere 3.7% of payouts in the reverse auction in spite of representing a large share of licensed broadcasters.

Table 3: Ownership concentration

	All 202 DMAs	119 positive demand DMAs (120 MHz)	79 positive demand DMAs (84 MHz)
Average across DMAs			
Number of licenses	8.27	9.24	9.62
Number of owners	6.49	7.32	7.61
Number of multi-license owners	1.25	1.40	1.53
Percentage of DMAs with j multi-license owners			
$j = 0$	38.6	32.8	31.7
$j = 1$	25.3	25.2	22.8
$j = 2$	19.8	25.2	25.3
$j = 3$	7.4	6.7	7.6
$j \geq 4$	8.9	10.1	12.7

the FCC.

5.1 Ownership concentration

Our data shows significant ownership concentration, both across and within DMAs, consistent with the notion of "chains" of TV stations. In 2015, the 1,670 TV stations are held by 482 owners. Of these 482 owners, 302 hold one TV station across the U.S., 66 hold two TV stations, 33 hold three TV stations, and the remaining 81 owners hold at least four TV stations. Turning to ownership concentration within DMAs, 78 DMAs have only single-license owners, meaning that all TV stations within the DMA are independently owned, while the remaining 124 DMAs have at least one multi-license owner, meaning that at least two TV stations within the DMA are jointly owned. Multi-license ownership within DMA is the focus of our main analysis in Sections 6 and 7, and we consider ownership across DMAs in Section 9.2.

Table 3 provides further details on ownership concentration, juxtaposing all 202 DMAs with the 119 positive demand DMAs for the 120 MHz clearing target and the 79 positive demand DMAs for the 84 MHz clearing target. As the top panel shows, on average across all DMAs, 6.49 owners hold 8.27 TV stations whereas on average across positive demand DMAs for the 120 MHz (84 MHz) clearing target, 7.32 (7.61) owners hold 9.24 (9.62) TV stations. The number of multi-license owners is 1.25 on average for all DMAs compared to 1.40 (1.53) for positive demand DMAs for the 120 MHz (84 MHz) clearing target. The distribution over ownership configurations in the bottom panel of Table 3 reinforces that ownership is more concentrated in positive demand DMAs. In 80 of 119, or 67% (54 of 79, or 68%) of positive demand DMAs for the 120 MHz (84 MHz) clearing target, there is at least one multi-license owner as compared to in 124 of 202, or 61% of all DMAs. Taken together, this shows that multi-license ownership is prevalent, especially in DMAs that may play a key role in the reverse auction.

Ownership concentration has traditionally been a concern for regulators. The FCC Local TV

Ownership Rules permit joint ownership of up to two TV stations in the same DMA if either their service contours do not overlap or at least one of them is not ranked among the top four TV stations in the DMA, based on the most recent audience share, and there are at least eight independently owned commercial or non-commercial full-power stations in the DMA. However, these rules do not apply to non-commercial, low-power, and satellite stations. Moreover, waivers can be—and have been—granted for failing or financially distressed TV stations.[44] For historical reasons these rules are oriented towards the business of operating TV stations that primarily generate revenue from advertising and therefore prevent broadcasters from gaining excessive market power in the market for advertising. However, as our data and analysis show, these rules do not preclude firms from amassing market power over broadcast spectrum. As a result, some firms may have been able to accumulate market power in the reverse auction through multi-license ownership.

5.2 Private equity firms

Some chains of TV stations are recent creations. From 2011 to 2015, three private equity firms — LocusPoint Networks, NRJ TV, and OTA Broadcasting (henceforth, LocusPoint, NRJ, and OTA) — acquired 48 UHF stations for at least $380 million.[45,46] Of the 48 TV stations, 15 are full-power stations, 33 are low-power class-A stations; 47 are commercial stations, and one is a non-commercial station. Few of the 48 TV stations are affiliated with major networks and many of them are failing or in financial distress. The trade press widely claimed that the private equity firms acquired TV stations with the goal of "flipping" them for profit in the reverse auction.[47]

Most of the acquired TV 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. The 48 TV stations are located in 21 DMAs that we refer to as private equity active DMAs. Of the 21 private equity active DMAs, 20 are positive demand DMAs under the 120 MHz clearing target and 18 are positive demand DMAs under the 84 MHz clearing target. In line with a goal of flipping TV stations, the private equity firms appear to have targeted DMAs with robust "demand". At the same time, however, the private equity firms accumulated market

[44]The rules are set out in paragraph (b) of Title 47 of the Code of Federal Regulations, Chapter I.C, Part 73.H, Section 73.3555, with carve-outs in paragraph (f), note (5), and note (7). See https://www.law.cornell.edu/cfr/text/47/73.3555, accessed on March 29, 2018. The Low Power Television (LPTV) Service Guide further exempts low-power stations. See https://www.fcc.gov/consumers/guides/low-power-television-lptv-service, accessed on March 29, 2018.

[45]According to FCC filings, the Blackstone Group LP owns 99% of LocusPoint. NRJ 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 is a division of MSD Capital LP, which was formed to manage the wealth of Dell Computer founder Michael Dell.

[46]LocusPoint acquired another 3 UHF stations for $4.8 million that it sold to HME Equity Fund II LLC for $23.75 million before the reverse auction. See http://www.tvnewscheck.com/article/92491/hme-equity-closes-on-purchase-of-3-lptvs, accessed on March 17, 2018. NRJ acquired another VHF station for $9.9 million. See http://www.tvnewscheck.com/article/89486/nrj-tv-buys-dallas-vhf-for-99-million, accessed on April 30, 2018.

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

Table 4: Comparison of TV stations acquired by private equity firms and other transactions from 2010 to 2013

	Private equity firms			Other transactions		
	Mean	Std. Dev.	Median	Mean	Std. Dev.	Median
Transaction price ($ million)	7.91	9.74	4.55	25.20	48.90	7.73
UHF	1	0	1	0.80	0.40	1
Commercial	0.98	0.14	1	0.98	0.13	1
Full-power	0.31	0.47	0	0.84	0.37	1
Major network	0.04	0.20	0	0.60	0.49	1
Broadcast volume (million)	0.28	0.16	0.28	0.17	0.13	0.14
Inference free population (million)	3.61	3.47	2.53	1.69	2.04	1.01
Interference count	104.10	35.41	101.50	79.44	47.35	72.50
Number of licenses		48			286	

power in the reverse auction. For example, NRJ acquired four TV stations in the Los Angeles, CA, DMA and OTA acquired eleven TV stations in the Pittsburgh, PA, DMA. The 10 TV stations acquired by LocusPoint are located in 10 different DMAs, the 15 TV stations acquired by NRJ are located in 10 different DMAs, and the 23 TV stations acquired by OTA are also located in 10 different DMAs.

Table 4 summarizes attributes of the 48 TV stations acquired by the three private equity firms and contrasts them with the 286 TV stations that were part of other transactions in the four years from 2010 to 2013. While there is considerable overlap in the distributions of transaction price and the other attributes between the two groups, the private equity firms acquired relatively cheaper TV stations. Moreover, these TV stations have higher broadcast volume, both because of higher interference free population and because of higher interference count. The 48 TV stations acquired by the three private equity firms are therefore relatively more difficult to assign to a channel in the repacking process if they opt to remain on the air. At the same time, the base clock price is "magnified" by the relatively high broadcast volume if these TV stations are frozen in the course of the reverse auction.

Perhaps even more telling, the private equity firms relinquished only 19 TV stations, or 40% of the acquired TV stations, in the reverse auction and sold another 26 TV stations, or 54% of the acquired TV stations, soon after the reverse auction. This appears difficult to reconcile with the goal of flipping TV stations. Table 5 further fleshes out acquisitions and sales. Separately for LocusPoint, NRJ, and OTA, the table provides the number of TV stations acquired before the reverse auction along with the amount paid, the number of TV stations relinquished in the reverse auction along with the amount received, and the number of TV stations sold soon after the reverse auction along with the amount received. The table finally indicates the profit made or loss incurred on these latter two sets of TV stations. We provide further details and the underlying data in Online Appendix C. While the private equity firms made—typically substantial—profits on the TV stations they relinquished in the reverse auction, they incurred losses on the TV stations they sold soon after.

Table 5: Private equity firms' acquisitions and sales of TV stations

	TV stations		
	acquired before reverse auction	relinquished in reverse auction	sold after reverse auction
LocusPoint			
Number	10	2	7
Amount ($ million)	55.85	15.20	27.00
Profit/loss ($ million)		8.80	-19.40
NRJ			
Number	15	7	7
Amount ($ million)	245.25	640.00	94.45
Profit/loss ($ million)		526.72	-3.5
OTA			
Number	23	10	12
Amount ($ million)	78.75	441.00	38.38
Profit/loss ($ million)		402.26	-1.64

While the activities of the three private equity firms are very salient, their contribution to ownership concentration is small: the private equity firms are just three of 180 owners, or 2%, that hold more than one TV station across the U.S., and they hold just 48 of 1,368 TV stations, or 4%, that belong to one of these chains. The vast majority of ownership concentration is long standing and reflects reasons that are orthogonal to the incentive auction, such as historical accident, advertising market, content provision, etc.

6 Analysis

We first describe how we estimate the reservation value of a TV station. With reservation values in hand, we conduct a large-scale simulation exercise to compare the outcome of the reverse auction under the counterfactual of independent ownership and 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.

6.1 Reservation values

In close resemblance to how market participants and industry consultants value a TV station,[48] we model the reservation value of TV station j in year t_0 as the greater of its cash flow value $v_{jt_0}^{CF}$ and its "stick" value $v_{jt_0}^{Stick}$:

$$v_{jt_0} = \max\left\{v_{jt_0}^{CF}, v_{jt_0}^{Stick}\right\}. \tag{6}$$

[48]See "Broadcasting M&A 101: Our View of the Broadcast TV M&A Surge", Davis Hebert and Eric Fishel, Wells Fargo, June 26, 2013 and "Estimating the Value of TV Broadcast Licenses for the Upcoming FCC Incentive Auction", Mark Mondello and Arya Rahimian, Duff & Phelps, November 23, 2015.

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 $Multiple^{CF}_{jt_0}$. Hence, the cash flow value of the TV station is

$$v^{CF}_{jt_0} = Multiple^{CF}_{jt_0} \cdot CF_{jt_0}. \tag{7}$$

This is the price the TV station expects if it sells itself on the private market as a going concern.

The stick value of the TV station, on the other hand, reflects solely the value of its license and broadcast tower, not the ongoing business. It is the default value of a non-commercial station and is computed from the population served and the stick multiple $Multiple^{Stick}_{jt_0}$. The stick multiple is traditionally expressed on a per MHz per population (henceforth, MHz-pop) basis. For a low-power class-A station, we use interference free population to measure population served. Hence, the stick value of a low-power class-A station is

$$v^{Stick}_{jt_0} = Multiple^{Stick}_{jt_0} \cdot 6\, MHz \cdot InterferenceFreePop_{jt_0}. \tag{8}$$

Because of the must-carry provision of the Cable Television Consumer Protection and Competition Act of 1992, a full-power station must be carried on any cable system operating in the same DMA.[49] We therefore use DMA population to measure population served. Hence, the stick value of a full-power station is

$$v^{Stick}_{jt_0} = Multiple^{Stick}_{jt_0} \cdot 6\, MHz \cdot DMAPop_{jt_0}. \tag{9}$$

While we observe the population served by a TV station, 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. We provide further details in Appendix C.

Cash flows. We model the cash flow CF_{jt} of TV station j in year t as

$$CF_{jt} = \alpha\left(X_{jt};\beta\right) AD_{jt} + RT\left(X_{jt};\gamma\right) - F\left(X_{jt};\delta\right) + \epsilon_{jt}, \tag{10}$$

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. Our estimation includes all TV

[49] More specifically, any cable operator offering more than 12 channels must set aside one third of its channels for local commercial broadcasters. Any cable operator offering more than 36 channels must carry all non-commercial and educational broadcasters.

stations covered by the aggregated data from NAB. The parameters $\theta = (\beta, \gamma, \delta, \sigma)$, together with our functional form and distributional assumptions in equation (10), imply a distribution of the cash flow CF_{jt} of TV station j 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, non-broadcast revenue, and fixed cost distributions to the moments reported by NAB for different sets of TV stations and DMAs. In particular, we match the mean along with the first, second, and third quartile of cash flow and the mean of non-broadcast revenue and fixed cost for each NAB table in each year, yielding a total of 3,976 moments.

Overall, the cash flow model in equation (10) fits the data well. The correlation between the moments of the predicted distributions at our estimates and the moments reported by NAB is between 0.97 and 0.99 for cash flow, 0.95 for non-broadcast revenue, and 0.96 for fixed cost

Multiples. To estimate the multiples $Multiple_{jt}^{CF}$ and $Multiple_{jt}^{Stick}$, we begin with 398 transactions for 655 TV stations in the 11 years from 2003 to 2013 that BIA records. We extract 230 transactions for 402 TV stations based on cash flow and 168 transactions for 253 stations based on stick value.[50] We infer the cash flow multiple and stick multiple from the transaction price, the population served, and the power output of the TV station using equations (7), (8), and (9), respectively. We project the log of these multiples on station, owner, and market characteristics X_{jt}, including year fixed effects to capture the secular decline in the use of broadcast TV. This allows us to predict multiples for any TV station, not just those that were recently transacted. Appendix C.2 details how we model the cash flow and stick multiples and the estimated distributions of these multiples for the 1,670 UHF stations located in the U.S. excluding Puerto Rico and the Virgin Islands that the FCC has declared as eligible for the reverse auction. In line with outside analysts estimates, we estimate a mean cash flow multiple of 10.22, with a standard deviation of 5.96, and a mean stick multiple of \$0.43 per MHz-pop, with a standard deviation of \$1.84, for the auction-eligible TV stations.[51]

Reservation values. The aggregated data from NAB that we use to estimate the cash flow model in equation (10) does not cover all 1,670 UHF stations located in the U.S. excluding Puerto Rico and the Virgin Islands that the FCC has declared as eligible for the reverse auction. The omissions are 387 low-power class-A stations, 289 non-commercial stations, and 4 dark stations

[50] BIA records 659 transactions with transaction prices, as opposed to station swaps, stock transfers, donations, etc. We exclude transactions for public stations, religious stations, and those with non-commercial owners. In identifying transactions based on cash flow, we further exclude transactions for dark stations and for stations with negative predicted cash flows and transactions with a purchase price below \$1 million. In case of multi-station deals, we exclude transactions for stations with widely varying cash flows to facilitate allocating the purchase price in proportion to the population covered by the included stations. Lastly, we exclude four transactions with a cash flow multiple in excess of 250. This leaves us with a sample of 230 transactions based on cash flow. In identifying transactions based on stick value, we include transactions for dark stations, for stations with negative predicted cash flows, and for stations that are not affiliated with a major network and have a purchase price of less than \$1 million. This leaves us with a sample of 168 transactions based on stick value.

[51] See Bond & Pecaro, "Opportunities And Pitfalls On The Road To The Television Spectrum Auction," 2013, and Wells Fargo, "Broadcasting M&A 101: Our View of the Broadcast TV M&A Surge," 2013.

that we henceforth subsume into non-commercial stations. We therefore extrapolate from our estimates as follows. First, we assume that low-power class-A 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 their stick value, consistent with industry practice.

To estimate the reservation value of TV station j going into the reverse auction, we set $t_0 = 2015$.[52] We draw from the estimated distribution of the cash flow error term ϵ_{jt_0} to get $\widehat{CF}_{jt_0}$ and scale it with the TV station's estimated cash flow multiple. Similarly, we scale the TV station's population served and the 6 MHz of its license with the TV station's estimated stick multiple.[53] As specified in equations (6)–(9), the reservation value $\widehat{v}_{jt_0}$ of a commercial station is then the higher of the realized draws of its cash flow value and its stick value; the reservation value $\widehat{v}_{jt_0}$ of a non-commercial station is its stick value.

In the subsequent analysis, we simulate the reverse auction for $N^s = 100$ draws of reservation values. On average across simulation draws, our estimates imply that the average commercial TV station has a cash flow value of \$57.4 million and that the average TV station has a stick value of \$6.0 million. For 29.2% of TV stations, the median reservation value is given by the stick value rather than the cash flow value as the former is higher, and the average TV station has a reservation value of \$51.1 million.

To illustrate our estimates, Figure 2 shows a sample draw of reservation values for the 24 TV stations in the Philadelphia, PA, DMA. We label the TV stations by their network affiliation, order them by their reservation values (left axis), and overlay their advertising revenues (right axis) in 2012 from the BIA data.[54] Reservation values correlate with advertising revenues and network affiliation. In addition, it is immediately apparent that reservation values can differ greatly across TV stations, even within a DMA, with few high value TV stations and a long tail of low value TV stations.

Validation. To validate our estimated reservation values and to provide further evidene of strategic supply reduction, we use the recently released data that records the price at which a participating TV station withdrew from the reverse auction. We regress these dropout points on a constant and our estimated reservation values, averaged across simulation draws, for various subsets of TV stations depending on their ownership structure. We start with all TV stations that withdrew from the reverse auction. Next we restrict attention to those TV stations that do not share an owner with another TV station in the same DMA, then to those TV stations that do not share an owner with another TV station in the same DMAs and its neighboring DMAs,[55] and finally to those TV stations that do not share an owner with another TV station across the U.S. Because truthful

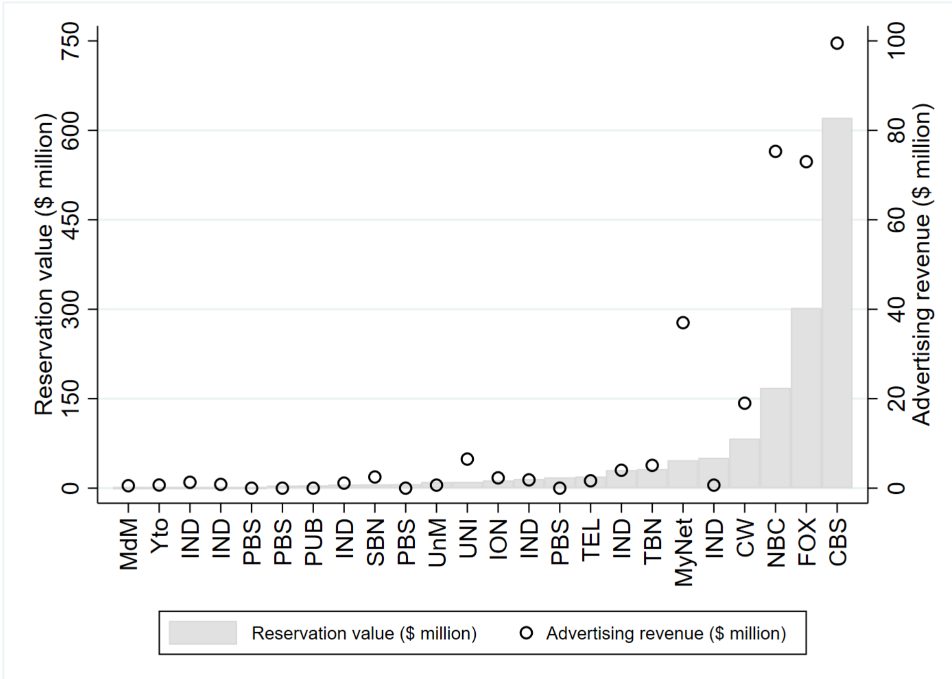
[52]Because the NAB data is only available through 2012, we cannot estimate a year fixed effect for 2015 and instead hold it fixed at the year fixed effect for 2012.

[53]We thus do not account for estimation error in the parameters of the cash flow model in equation (7) and the multiples models in Appendix C.2.

[54]WPVI-TV (facility ID 8616), the Philadelphia ABC affiliate, is a VHF station and therefore not included in Figure 2.

[55]We formally define a region around a DMA in Section 6.2.

Figure 2: Sample draw of reservation values for TV stations in Philadelphia, PA, DMA



bidding is a dominant strategy for an independently owned TV station, we expect the coefficient on the constant to approach zero and the coefficient on the estimated reservation value to approach one as we narrow the set of TV stations.

We proceed separately for TV stations that we assign a cash flow value in the majority of simulation draws and TV stations that we assign a stick value. Table 6 reports the estimates along with an F-test that the coefficient on the estimated reservation value is one. The left panel pertains to the sample of cash-flow-valued stations, the right panel to the sample of stick-valued stations, and the four columns in each panel correspond to the progression from all TV stations that withdrew from the reverse auction to the subset of TV stations that do not share an owner with another TV station across the U.S. For the sample of cash-flow-valued stations, the coefficient on the constant as expected approaches zero and the coefficient on the estimated reservation value approaches one as we narrow the set of TV stations. This is not the case for the sample of stick-valued stations, although our estimated reservations values are strongly positively correlated with the dropout points.

We conclude that our estimated reservations values are, on average, informative about true reservation values as given by the dropout points of independently owned TV stations, especially for cash-flow-valued stations. At the same time, our estimated reservation values can differ considerably from the dropout points for individual TV stations. KCBS-TV, the flagship CBS affiliate on the West Coast, is an extreme example, with an estimated reservation value of $3,293 million and a dropout point of $205 million.[56] It is perhaps not surprising that our estimated reservation values

[56] We drop KCBS-TV from teh sample of cash-flow-valued stations in Table 6.

Table 6: Regression of dropout points on constant and estimated reservation values

	Cash-flow-valued stations				Stick-valued stations			
		No shared owner				No shared owner		
	All	within DMA	within DMA and neighbors	across U.S.	All	within DMA	within DMA and neighbors	across U.S.
Constant	26.81***	12.95***	10.97***	7.389	5.517	-1.703	0.792	-14.53
	(3.245)	(4.356)	(4.645)	(6.203)	(6.803)	(6.390)	(8.833)	(10.46)
Estimated	0.690***	1.561***	1.101***	1.141***	4.249***	4.665***	3.378***	8.263***
res. value	(0.059)	(0.113)	(0.129)	(0.227)	(0.495)	(0.519)	(0.748)	(1.216)
Adj. R^2	0.206	0.362	0.286	0.207	0.273	0.341	0.197	0.480
N	528	336	183	99	198	158	85	52
Test of coefficient on estimated reservation value is one								
$F(1, N-2)$	27.63	24.42	0.61	0.39	43.05	49.91	10.11	36.65
p-value	0.000	0.000	0.435	0.534	0.000	0.000	0.002	0.000

are less informative for stick-valued stations than for cash-flow-valued stations given the paucity of data that is available on non-commercial stations. Taken together, the noise in our estimated reservation values appears too large to allow us to compare the outcome of the reverse auction with the predictions of our model at the level of individual TV stations.

6.2 Simulation exercise

As described in Section 2, the repacking process takes place at the national level. Through a series of domino effects in the interference constraints, it is possible, although perhaps unlikely, that as a TV station in New York, NY, opts to remain on the air, it freezes a TV station in Los Angeles, CA, that can no longer be guaranteed a channel in the next round of the reverse auction. Checking the feasibility of repacking a set X of TV stations into a set R of available channels is a computationally challenging (NP-hard) problem that can easily take hours to run. Indeed, despite its considerable computational resources, on June 14, 2016 the FCC had to delay round 22 of stage 1 of the reverse auction because it failed to solve the problem on time.[57]

Our goal is to enumerate all equilibria of the reverse auction in order to assess the scope for strategic supply reduction and quantify its impact on the outcome of the reverse auction. To do so, we simulate the reverse auction under the very large number of strategy profiles that arise because of the large number of jointly owned TV stations, each of which has the strategy space $b_j \in \{0, s_j, 900\}$ (see Section 3). Moreover, we repeat these simulations for $N^s = 100$ draws of reservation values to account for randomness. In contrast, the FCC ran the reverse auction only one time, pausing occasionally to move to the forward auction and assess the final stage rule.

As a step towards making the analysis computationally feasible, we take a regional approach to the repacking problem as follows: given a "focal" DMA, we define its "region" as the set of all DMAs in which at least one TV station has an interference constraint with at least one TV station in the focal DMA. We simulate the reverse auction restricting the repacking problem to TV stations in the region.[58] This breaks up the national problem into multiple regional problems, one for each focal DMA. Our regional approach is in line with the fact that the FCC's feasibility checker $SATFC$ prioritizes local solutions to the repacking problem, holding fixed the assignments of TV stations with no direct interference constraint with a TV station that is being repacked while looking for a new solution (Frechette, Newman and Leyton-Brown, 2016, Section 4.1).[59] Throughout, the object of interest is the outcome of the reverse auction in the focal DMA, which we then aggregate to the national level for a given draw of reservation values.

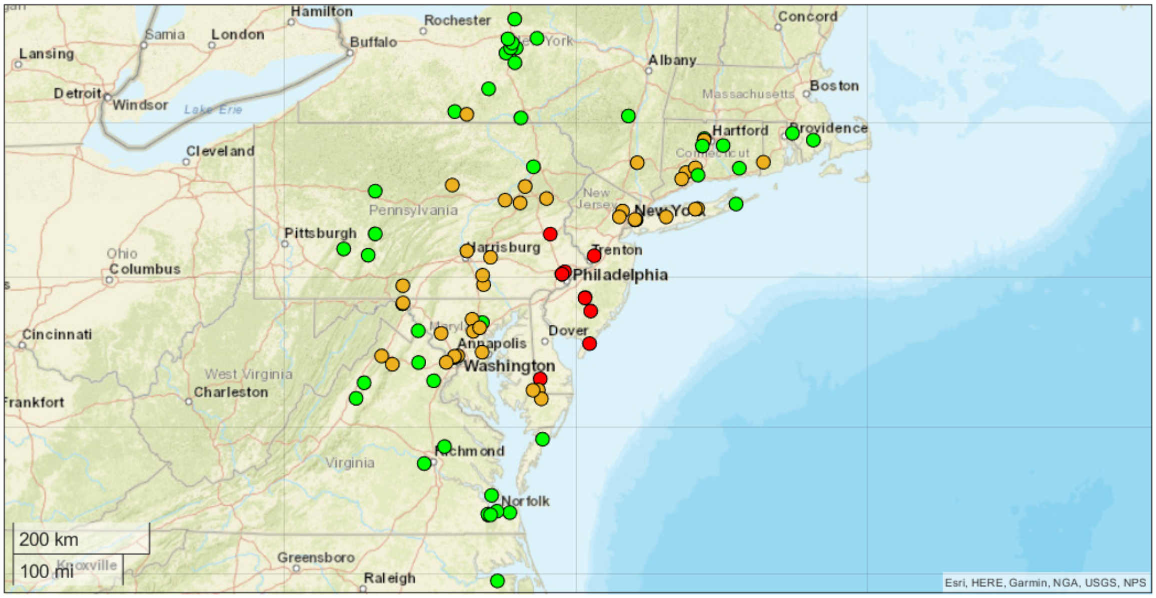
We base our definition of a region on the interference constraints for the 1,670 UHF stations and UHF channels 14-29 that are available for repacking under the 126 MHz clearing target. This

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

[58] To speed up the computations and decrease the amount of memory overhead required for large-scale parallel computing, we use Perl scripts to create region-specific domain and pairwise interference files.

[59] See also http://conference.nber.org/confer/2017/AIf17/Milgrom_Tadelis.pdf, accessed on March 18, 2018.

Figure 3: Repacking region for Philadelphia, PA, DMA



Notes: Dots denote facility locations. Red dots denote TV stations in the Philadelphia, PA, DMA; yellow dots TV stations in other DMAs that have at least one interference constraint with a TV station in the Philadelphia, PA, DMA; and green dots TV stations in other DMAs in the repacking region that do not have an interference constraint with a TV station in the Philadelphia, PA, DMA.

definition is invariant to alternative clearing targets. Figure 3 shows the 162 TV stations located in the Philadelphia, PA, region. Of those, 24 are in the Philadelphia, PA, DMA (denoted by red dots in Figure 3), while 138 are located outside the Philadelphia, PA, DMA (yellow and green dots) in one of the following DMAs: New York, NY, Washington, DC, Baltimore, MD, Hartford-New Haven, CT, Norfolk-Portsmouth-Newport News, VA, Harrisburg-Lancaster-Lebanon-York, PA, Providence, RI-New Bedford, MA, Wilkes Barre-Scranton, PA, Richmond-Petersburg, VA, Syracuse, NY, Johnstown-Altoona, PA, Salisbury, MD, Binghamton, NY, Elmira, NY, and Harrisonburg, VA. Moreover, 63 of the TV stations located outside the Philadelphia, PA, DMA do not have an interference constraint with any TV station located inside the Philadelphia, PA, DMA (green dots); they are nevertheless part of the Philadelphia, PA, region and may thus affect the price for a TV station in the Philadelphia, PA, DMA.

Table 7 covers all 202 DMAs and shows that a region is generally much larger than a DMA. We compare a focal DMA to its region in terms of number of TV stations and area in square miles.[60] On average, a region covers about 11 DMAs. It has about 19 times as many TV stations and is about 18 times larger in area than the focal DMA.[61]

Beyond repacking regions, a further input into the simulations is the set of participating stations.

[60]See Sood (2018) for a crosswalk between DMAs and zip codes. We obtain zip code area from the Missouri Census Data Center, MABLE/Geocorr14: Geographic Correspondence Engine, at http://mcdc.missouri.edu/websas/geocorr14.html, accessed on July 22, 2018.

[61]Five DMAs coincide with their region. These are Anchorage, AK, Casper-Roverton, WY, Eureka, CA, Fairbanks, AK, and Honolulu, HI.

Table 7: Repacking regions for all 202 DMAs

	Mean	Min	Quartile First	Quartile Second	Quartile Third	Max
Number of DMAs per region	11.6	1	6	12	17	26
Ratio between region and focal DMA						
Number of TV stations	18.77	1	6.9	13.6	21.6	160
Area (square miles)	18.1	1	7.8	14.0	21.4	170.3

Of the 1,670 auction-eligible TV stations, the FCC declared 247 TV stations that can always be assigned a UHF channel under any possible clearing target as "not needed" for the reverse auction and bars them from participating.[62] In our model of the reverse auction, not participating is equivalent to fully overbidding.

We assume that the remaining 1,423 TV stations participate in the reverse auction. As the recently released data on participation and bids in the reverse auction show, this overstates participation. The FCC has long worried that potentially "sentimental" owners, in particular, of religious or college-affiliated stations may be motivated by considerations besides profitability and not participate in the reverse auction.[63] In the popular press, several chains of commercial TV stations have shown little interest in the reverse auction, with the CEO of Sinclair Broadcasting Group, which operates 98 of the 1,670 auction-eligible TV stations in 2015, declaring that he "hasn't heard of any broadcaster who has said they have anything for sale."[64] In Section 9.1 we show that reduced participation can nearly double payouts in the reverse auction, even in the absence of strategic supply reduction. The assumption of full participation underlying our main results is therefore conservative.

Our baseline is the outcome of the reverse auction under naive bidding, where we ignore the ownership patterns in the data and counterfactually treat all TV stations as independently owned. Hence, TV station j bids $b_j = s_j = \frac{v_j}{\varphi_j}$, where v_j is its reservation value and φ_j its broadcast volume (unless TV station j is not needed and we set its bid to $b_j = 900$). We simulate the reverse auction under naive bidding for $N^s = 100$ draws of reservation values. In Online Appendix D, we provide pseudo code for our algorithm.

We contrast naive bidding with strategic bidding, where we account for the ownership patterns in the data and allow the owner of a jointly owned TV station j located inside the focal DMA to either bid truthfully $b_j = s_j$ or overbid $b_j = 900$. While Example 2 in Section 3.1 shows that underbidding $b_j = 0$ can also be part of an equilibrium of the reverse auction, we rule out

[62] See http://wireless.fcc.gov/auctions/incentive-auctions/Reverse_Auction_Opening_Prices_111215.xlsx, and Paragraph 6 of FCC Public Notice DA 16-453 available at https://apps.fcc.gov/edocs_public/attachmatch/DA-16-453A1.pdf, accessed on March 7, 2018. The FCC additionally declared KLHU-CD (facility ID 30932) as not needed but revoked its license prior to the reverse auction, see footnote 13.

[63] See http://www.tvnewscheck.com/article/73196/wheeler-auction-onceinalifetime-chance, accessed on March 18, 2018.

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

underbidding as a strategy in the simulation exercise to reduce the computational burden.[65] To limit the number of strategy profiles that arise, we assume that a TV station j located outside the focal DMA bids truthfully $b_j = s_j$ (again, unless TV station j is not needed and we set its bid to $b_j = 900$).[66] This assumption is conservative in that it restricts a multi-license owner's ability to strategically reduce supply to the focal DMA. In Section 9.2 we show that abandoning this assumption and allowing for multi-market strategies can greatly increase the scope for strategic supply reduction and the payouts in the reverse auction.

To simulate the reverse auction under strategic bidding, we modify our algorithm. Recall that, as the reverse auction progresses, each time an active TV station opts to remain on the air, the FCC invokes $SATFC$ to check if it can still repack any remaining active TV station. We limit this check to any remaining active TV station located in the focal DMA. We further pre-assign to frozen status any TV station located outside the focal DMA that has been frozen at the conclusion of the reverse auction under naive bidding; these TV stations therefore cannot freeze another TV station. In Online Appendix D, we provide pseudo code for the modified algorithm. The primary advantage of this limited repacking is that the computational burden, while still significant as we discuss below, falls by a factor of nearly 10 relative to full repacking.[67] In Appendix D we show that nationwide payouts under limited repacking differ from those under full repacking by 0.2% under naive bidding and the 126 MHz clearing target and by 1.5% under naive bidding and the 84 MHz clearing target, reflecting the larger amount of repacking that occurs under the 84 MHz clearing target as more TV stations remain on the air. Simulations for the New York, NY, DMA under strategic bidding suggest a similar error.

Given a draw of reservation values, we determine that a strategy profile is an equilibrium of the reverse auction if no multi-license owner can unilaterally and profitably deviate to another strategy profile. We use the same $N^s = 100$ draws of reservation values as above. With no or one multi-license owner in a DMA, there is a unique equilibrium by construction. With more than one multi-license owner, there may be multiple equilibria, and we enumerate all of them. We discard equilibria that entail a failure at the outset (see footnote 28) as these are of little practical relevance. Given the large number of equilibria and the fact that many of them entail identical payouts to all TV stations despite possibly differing bids, we limit attention to "payout-unique equilibria." That is, we collapse multiple equilibria with identical payouts to all TV stations into a single payout-unique equilibrium. We illustrate this concept further in discussing our results in Section 7.

Despite the numerous assumptions and simplifications, our simulation exercise is near the bound of what can be achieved in a reasonable amount of time. The 1,670 auction-eligible TV stations are located in 202 DMAs. Table 8 lists the top ten computationally most demanding DMAs. It

[65] In Online Appendix E, we investigate the importance of underbidding for the computationally manageable New York, NY, DMA. We show that allowing for underbidding has a small impact on payouts.

[66] We further assume that a multi-license owner does not overbid $b_j = 900$ on all its TV stations j that are located inside the focal DMA.

[67] For comparison, under naive bidding and the 84 MHz clearing target, the average time for a simulation of the reverse auction under full repacking is 1206.18 seconds and 191.17 seconds under limited repacking.

Table 8: Top ten computationally most demanding DMAs

DMA	TV stations	Multi-license owners	Jointly owned TV stations	Strategy profiles
Pittsburgh, PA	23	3	16	42,987
Santa Barbara, CA	16	4	12	2,205
San Francisco, CA	24	6	13	1,701
Philadelphia, PA	24	6	12	729
Washington, DC	19	5	11	567
Fort Smith, AR	14	4	10	405
Los Angeles, CA	28	4	11	405
Austin, TX	16	1	9	255
Grand Rapids, MI	13	1	8	255
Boston, MA	20	4	9	189

provides the number of TV stations, the number of multi-license owners and the number of jointly owned TV stations in the focal DMA and its region, along with the number of strategy profiles to be considered. Because of not needed TV stations, 103 of the 124 DMAs with at least one multi-license owner have more than one strategy profile. The Pittsburgh, PA, DMA has 42,987 strategy profiles, each of which requires a run of the "regionalized" reverse auction for each simulation draw. Across all 202 DMAs, the total number of strategy profiles is 52,356. Scaling this up by $N^s = 100$ draws of reservation values requires 5,235,600 runs of the reverse auction. To give a sense of the computational burden of our exercise, we note that simulating the reverse auction under the 84 MHz clearing target for those 5,235,600 runs alone required a total of 23,710 CPU-days.

7 Results

7.1 Case study: Philadelphia, PA, DMA

We use the Philadelphia, PA, DMA as a case study to illustrate how we compare the outcome of the reverse auction under naive bidding with the outcome under strategic bidding and to highlight important features of the subsequent analysis. Figure 4 shows the sample draw of reservation values from Figure 2 for the 24 TV stations in the Philadelphia, PA, DMA along with the outcomes of the reverse auction for the 126 MHz clearing target, contrasting outcomes under naive bidding in panel (a) and under two equilibria with strategic bidding in panels (b) and (c). All panels show reservation values and payouts (in $ million) in light and dark gray, respectively, on the left axis. As in Figure 2, we label the TV stations by their network affiliation and order them by their reservation values. We additionally indicate multi-license ownership using symbols in brackets to distinguish between owners. On the right axis, we account for the broadcast volumes of the TV stations and display their corresponding bids and payouts in terms of the base clock price as rectangles and triangles, respectively. Recall from Section 3 that a bid is the critical value of the base clock price above which a TV station continues in the reverse auction.

Panel (a) of Figure 4 shows the outcome under naive bidding. 17 TV stations relinquish their licenses in exchange for payment. The FCC pays a total of $1,004.54 million to acquire TV stations with combined reservation values of $177.69 million. NRJ, in particular, owns the independent station WTVE (facility ID 55305, reservation value $15.26 million) and the Youtoo America affiliate WPHY-CD (facility ID 74464, reservation value $0.23 million) in the Philadelphia, PA, DMA. Under naive bidding, NRJ sells both TV stations. Its profit, the total proceeds from the reverse auction less the reservation values of the surrendered stations, is $95.02 million.

Panels (b) and (c) visualize two equilibria, where we identify TV stations that are withheld from the reverse auction with bids of 900. The first equilibrium highlights that strategic supply reduction by multi-license owners can lead to more TV stations being sold under strategic bidding than under naive bidding. The second equilibrium highlights that strategic supply reduction can lead to the same TV stations being sold, but at higher prices. As we illustrate in Section 7.2, instances of the second equilibrium are more common than instances of the first equilibrium. In what follows, we provide further details on these equilibria.

Equilibrium 1: More TV stations sell. In this equilibrium, NRJ withholds WPHY-CD from the reverse auction. Similarly, the NJ Public Broadcasting Authority withholds WNJS (facility ID 48481), one of the two TV stations it owns in the Philadelphia, PA, DMA. Nevertheless, more TV stations sell than under naive bidding: while WPHY-CD and WNJS sell under naive bidding but not under strategic bidding, four TV stations—the CW affiliate WPSG (facility ID 12499), the My Network TV affiliate WPHL-TV (facility ID 73879), and the two independent stations WMCN-TV (facility ID 9739) and WQAV-CD (facility ID 191822)—sell under strategic bidding but not under naive bidding.

NRJ increases its profit through strategic supply reduction. Relative to naive bidding, NRJ foregoes a payout of $40.87 million, translating into a foregone profit of $40.64 million, on WPHY-CD. In return, NRJ collects an additional payout and thus profit of $210.13 million on WTVE, driven by an increase in the freezing base clock price from 129.34 to 519.56. Strategic supply reduction similarly increases the payout to the NJ Public Broadcasting Authority, as well as to several other TV stations that continue to bid naively. Payouts in the Philadelphia, PA, DMA increase from $1,004.54 million for 17 TV stations under naive bidding to $4,007.41 million for 19 TV stations with combined reservation values of $340.78 million in this equilibrium under strategic bidding.

Equilibrium 2: Same TV stations sell. In this equilibrium, Local Media TV Holdings withholds the independent station WQAV-CD and CBS withholds the CW associate WPSG from the reverse auction. The same TV stations sell as under naive bidding, but at weakly higher prices. Local Media TV Holdings experiences an increased profit of $34.62 million from selling its other independent station WTSD-CD (facility ID 191340). While the payout to CBS does not change, overall, payouts in the Philadelphia, PA, DMA increase from $1004.54 million to $1546.56 million for the same 17 TV stations as under naive bidding.

Figure 4 illustrates the reverse auction for just one sample draw of reservation values and two of the multiple equilibria that arise under strategic bidding. In the Philadelphia, PA, DMA, the average number of payout-unique equilibria across simulation draws is 2.62, ranging from one to eleven. On average, one payout-unique equilibrium summarizes 11.9 underlying equilibrium strategy profiles. In the subsequent analysis, we therefore repeat the above exercise for all 202 DMAs, accounting for randomness in the estimated reservation values via simulation and enumerating all payout-unique equilibria.

7.2 Naive versus strategic bidding

In comparing the outcomes of the reverse auction under naive and strategic bidding across all 202 DMAs we have to account for the fact that there may be multiple payout-unique equilibria in a given DMA under strategic bidding. Under the 84 MHz clearing target, there are 1.19 payout-unique equilibria on average across DMAs and simulation draws, ranging from 1 to 41. For the 103 DMAs with more than one strategy profile, the average number of payout-unique equilibria is 1.38. On average, one payout-unique equilibrium summarizes 34.3 underlying equilibrium strategy profiles.[68]

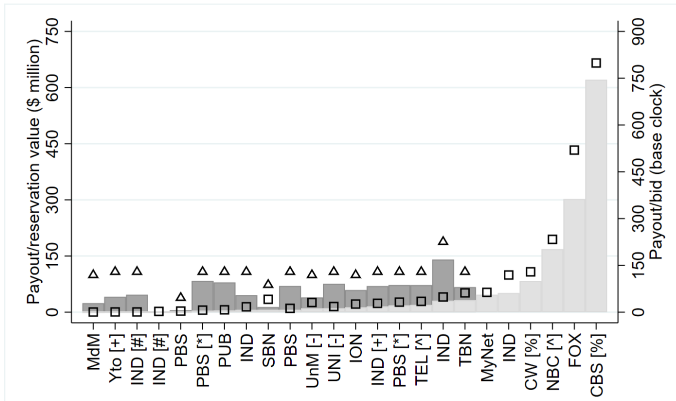
In many of the equilibria under strategic bidding, strategic supply reduction plays no role: on average across DMAs and simulation draws, there are just 0.49 payout-unique equilibria that have payouts that differ from those under naive bidding and the 84 MHz clearing target. At the same time, however, there is significant heterogeneity across DMAs in the prevalence of payout-unique equilibria that are sustained only by strategic supply reduction, in line with our result below that the impact of strategic supply reduction on payouts is concentrated in a select set of DMAs. Consider, for example, Pittsburgh, PA, the DMA with the largest number of strategy profiles. Out of 42,987 strategy profiles, on average across simulation draws, 65.3 are equilibria. These 65.3 equilibria amount to an average of 2.76 payout-unique equilibria, 2.70 of which have payouts that differ from those under naive bidding.

To account for multiple payout-unique equilibria in a given DMA, we report on an aggregate outcome of interest such as nationwide payouts, payouts to different types of owners, or the number of TV stations acquired by the FCC as follows: for a given DMA, we first record the mean, minimum, median, and maximum of the outcome of interest across all payout-unique equilibria for a given draw of reservation values. We then sum these moments across DMAs as needed to get to the national level. Finally, we average these sums across simulation draws. We also calculate standard deviations across simulation draws. Comparing the min and the max gives a sense of the importance of multiple equilibria. For the sake of brevity, in what follows we often just report the mean of an

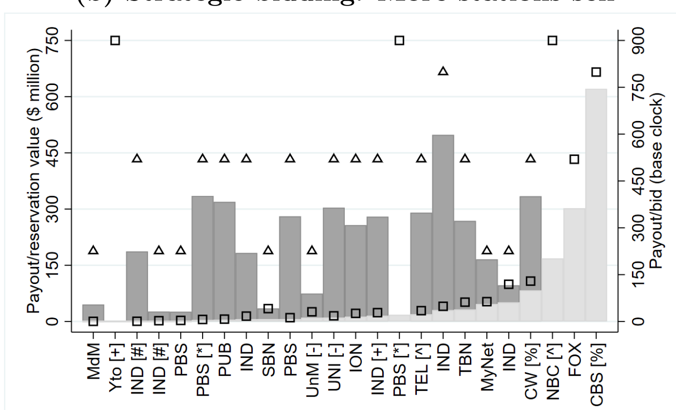
[68] The existence of a pure strategy equilibrium under strategic bidding is not guaranteed. In addition, as described in Section 6.2, we discard equilibria that entail a failure at the outset. As a result, in 0.04% of runs of the reverse auction, corresponding to nine simulations in four out of 202 DMAs, there is no pure strategy equilibrium under strategic bidding at the 84 MHz clearing target, and there is no pure strategy equilibrium in 0.22% of runs of the reverse auction under the 126 MHz clearing target. If there is no pure strategy equilibrium under strategic bidding, then we revert to naive bidding.

Figure 4: Sample outcome for Philadelphia, PA, DMA, 126 MHz clearing target

(a) Naive bidding



(b) Strategic bidding: More stations sell



(c) Strategic bidding: Same stations sell

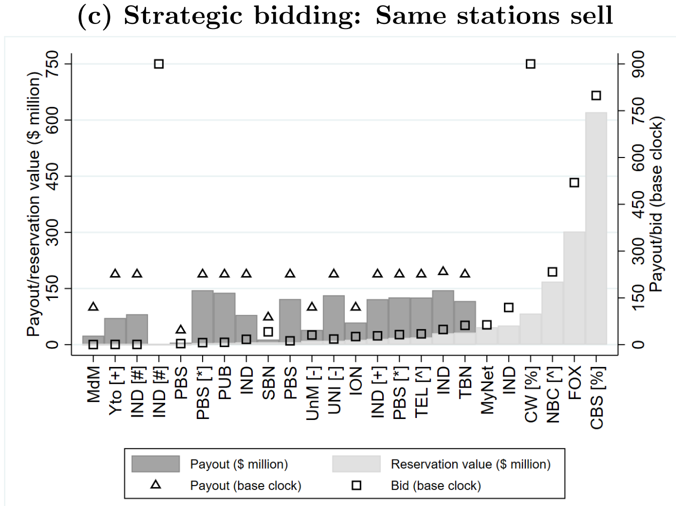


Table 9: Payouts to TV stations nationwide and by owner type

Payouts ($ billion)	Naive bidding	Strategic bidding Mean	Min	Median	Max	Payout increase at mean (%)
Panel A: 126 MHz clearing target						
Nationwide (202 DMAs)	15.767	22.457	20.440	22.292	24.702	42.4
	(2.639)	(3.898)	(4.097)	(4.024)	(4.198)	
Single-license owners	10.463	14.706	13.283	14.595	16.293	40.5
	(1.856)	(2.677)	(2.764)	(2.767)	(2.930)	
Multi-license owners	5.304	7.751	7.122	7.693	8.455	46.1
	(0.986)	(1.407)	(1.478)	(1.436)	(1.508)	
Panel B: 84 MHz clearing target						
Nationwide (202 DMAs)	2.477	2.812	2.679	2.810	2.952	13.5
	(0.361)	(0.420)	(0.402)	(0.426)	(0.453)	
Single-license owners	1.643	1.856	1.764	1.854	1.955	12.9
	(0.281)	(0.322)	(0.304)	(0.326)	(0.355)	
Multi-license owners	0.834	0.956	0.909	0.956	1.004	14.6
	(0.159)	(0.173)	(0.177)	(0.175)	(0.175)	

Notes: Payouts to single- and multi-license owners add to nationwide payouts for mean (up to rounding error) but not for min, median, and max. Payout increase at mean calculated as percent difference between mean payouts under strategic and naive bidding. Using $N^S = 50$ simulation draws for Pittsburgh, PA, DMA under 84 MHz clearing target.

outcome of interest.

Payouts. Table 9 shows payouts to TV stations in the reverse auction under naive and strategic bidding and both the 84 MHz and the 126 MHz clearing targets, first nationwide and then broken down for single- and multi-license owners.[69] Independent of the clearing target, strategic bidding raises nationwide payouts in the reverse auction. At the mean, strategic bidding increases nationwide payouts from $15.767 billion to $22.457 billion for the 126 MHz clearing target, an increase of 42.4%, and from $2.477 billion to $2.812 billion for the 84 MHz clearing target, an increase of 13.5%.

The reduced scope for strategic bidding to raise nationwide payouts under the 84 MHz clearing target reflects the skewed distribution of reservation values we illustrate in Figure 2 for the Philadelphia, PA, DMA. Under the lower clearing target, the number of TV stations acquired falls: we find that under strategic bidding on average across payout-unique equilibria and simulation draws, 452.02 TV stations are acquired to meet the 126 MHz clearing target, but only 190.35 TV stations are acquired to meet the 84 MHz clearing target. Under the lower clearing target, the "marginal" TV station is in a flatter portion of the distribution of reservation values; as a result, withholding a TV station from the reverse auction has a smaller impact on payouts.

[69] In contrast to Section 5.1, in what follows we define a multi-license owner as a firm owning more than one TV station within the focal DMA.

The remaining rows in Table 9 break down payouts for single- and multi-license owners. The payout increase from strategic bidding for multi-license owners is 46.1% and 14.6% under the 126 MHz and 84 MHz clearing targets, respectively. This spills over to single-license owners, who do not engage in strategic supply reduction, but see a payout increase of 40.5% or 12.9% depending on the clearing target.

Heterogeneity in payouts. There is significant heterogeneity in payouts across DMAs. First of all, in many DMAs the FCC does not acquire any TV stations: there are an average of 77 and 140 DMAs that see payouts of zero across simulation draws under naive bidding and the 126 MHz and 84 MHz clearing targets, respectively. Among the remaining DMAs, payouts are highly skewed. To illustrate, the 21 private equity active DMAs contribute 82.7% of nationwide payouts under naive bidding and the 84 MHz clearing target. The ten DMAs listed in Table 10 similarly account for $2.019 billion or 81.5% of nationwide payouts under the 84 MHz clearing target.

The payout increases due to strategic bidding are equally concentrated, as Table 10 shows. The table displays the top ten DMAs in terms of gains from strategic bidding under the 84 MHz clearing target. The Los Angeles, CA, DMA accounts for 46.7% of the average gains from strategic bidding; the next three most significant DMAs contribute 27.9%. In all, the top ten markets generate 96.5% of the average gains from strategic bidding. Private equity firms are active in seven of these ten DMAs, with the exception of Washington, DC, Hartford-New Haven, CT, and Burlington-Plattsburgh, NY, although these markets are adjacent to other DMAs where they control licenses. While we do not present the breakdown, payouts and gains from strategic bidding under the 126 MHz clearing target are similarly concentrated in a small number of DMAs.

To further investigate the sources of gains from strategic bidding, we decompose the DMA-level and nationwide gains into gains accruing to TV stations that sell under both naive and strategic bidding (labeled "always selling" in Table 11), to TV stations that sell only under strategic bidding ("newly selling"), and to TV stations that sell only under naive bidding ("no longer selling"). Table 11 reports this decomposition for the 84 MHz clearing target along with the number of TV stations in each of the three categories, averaged across payout-unique equilibria and simulation draws. Across the ten DMAs listed, TV stations that sell under both naive and strategic bidding account for between 20.02% and 101.91% of payout increases, with an average of 77.70% across DMAs. Similarly, at the national level, always selling TV stations garner 79.86% of payout increases. The right panel of Table 11 shows that there are very few TV stations that sell only under strategic bidding or only under naive bidding; the vast majority of TV stations (96.49% of the TV stations that sell under naive bidding at the national level) sell under both forms of bidding.

This suggests that in many equilibria strategic supply reduction does not significantly change the number and identity of the TV stations that sell, but increases the price at which these TV stations sell, similar to the second equilibrium in Section 7.1. Indeed, the average freezing base clock price indicates such price increases: we find that under naive bidding and the 84 MHz clearing target, the average freezing base clock price is $31.97, compared to $33.18 under strategic bidding.

Table 10: Payout gains from strategic bidding in top ten DMAs, 84 MHz clearing target

DMA	Payouts ($ billion)		Cumulative payout increase (%)
	Naive bidding	Payout increase	
Los Angeles, CA	0.906	0.156	46.7
Philadelphia, PA	0.285	0.051	62.0
New York, NY	0.373	0.042	74.6
San Francisco, CA	0.155	0.024	81.9
Washington, DC	0.077	0.016	86.7
Pittsburgh, PA	0.011	0.010	89.6
Chicago, IL	0.079	0.008	92.0
Hartford, CT	0.061	0.007	94.2
Boston, MA	0.066	0.005	95.6
Burlington, VT	0.006	0.003	96.5
Top ten DMAs	2.019	0.322	96.5
Nationwide	2.477	0.334	

Notes: Payout increase due to strategic bidding calculated as difference between mean payouts under strategic and naive bidding. Cumulative payout increase is the cumulative share of nationwide payout increases due to strategic bidding in the DMA under consideration and all DMAs with larger payout increases. Using $N^S = 50$ simulation draws for Pittsburgh, PA, DMA.

Table 11: Decomposition of payout gains from strategic bidding in top ten DMAs by type of TV station, 84 MHz clearing target

	Payout change ($ billion)				Number of TV stations			
DMA	Overall	Always selling	Newly selling	No longer selling	Total	Always selling	Newly selling	No longer selling
Los Angeles, CA	0.156	0.121	0.051	−0.010	28	10.460	1.030	0.360
Philadelphia, PA	0.051	0.038	0.020	−0.005	24	11.020	1.570	0.220
New York, NY	0.042	0.040	0.012	−0.009	25	10.330	0.640	0.230
San Francisco, CA	0.024	0.022	0.006	−0.002	24	9.150	0.610	0.120
Washington, DC	0.016	0.013	0.006	−0.001	19	6.590	1.040	0.220
Pittsburgh, PA	0.010	0.007	0.005	−0.001	23	5.340	2.320	1.100
Chicago, IL	0.008	0.006	0.003	−0.001	21	5.730	0.230	0.050
Hartford, CT	0.007	0.007	0.002	−0.002	11	4.690	0.400	0.110
Boston, MA	0.005	0.004	0.001	−0.000	20	6.220	0.320	0.070
Burlington, VT	0.003	0.001	0.004	−0.002	11	1.670	1.800	0.380
Top ten DMAs	0.322	0.259	0.109	−0.033	206	71.200	9.960	2.860
Nationwide	0.334	0.267	0.120	−0.039	1670	174.050	18.200	4.720

Notes: Payout change due to strategic bidding calculated as difference between mean payouts under strategic and naive bidding. For a given simulation draw and payout-unique equilibrium, we classify a TV station as always selling if it sells under both naive and strategic bidding, as newly selling if it sells only under strategic bidding, and as no longer selling if it only sells under naive bidding. Using $N^S = 50$ simulation draws for Pittsburgh, PA, DMA.

Under the 126 MHz clearing target, the respective prices are $80.28 and $109.93.

Efficiency losses from strategic bidding. The FCC acquires TV stations with a combined reservation value of $4.216 billion under strategic bidding and the 126 MHz clearing target in exchange for payouts of $22.457 billion, on average across payout-unique equilibria and simulation draws, and the FCC acquires TV stations with a combined reservation value of $0.895 billion under strategic bidding and the 84 MHz clearing target in exchange for payouts of $2.812 billion.

There are potential efficiency losses from strategic bidding by multi-license owners to the extent that such behavior distorts the set of TV stations that relinquish their licenses in the reverse auction. As we cannot easily ascertain the social value of the re-purposed spectrum, we adopt a notion of constrained efficiency, similar to Milgrom and Segal (2020). In comparing two outcomes of the reverse auction for the same clearing target, we treat as the more efficient one the outcome that has the lower total reservation value of acquired TV stations or, equivalently, the higher total reservation value of TV stations that remain on the air.[70] Not surprisingly, given the results in Table 11, we find that the total reservation value of acquired TV stations under naive and strategic bidding are very similar under both the 84 MHz and the 126 MHz clearing target. This reflects in

[70] This notion of constrained efficiency suffers of a number of shortcomings. We use the estimated private reservation value of a TV station in lieu of its social value. This in particular neglects consumer surplus, e.g., due to broadcast variety, to the extent that it is not appropriated by the TV station.

Table 12: Number of essential TV stations

	Strategic bidding			
	Mean	Min	Median	Max
Panel A: 126 MHz clearing target				
Number of essential TV stations	38.041	24.200	38.130	51.670
	(4.680)	(4.367)	(4.741)	(6.571)
Panel B: 84 MHz clearing target				
Number of essential TV stations	26.112	12.240	25.705	40.790
	(4.973)	(3.269)	(5.154)	(8.591)

Notes: Using $N^S = 50$ simulation draws for Pittsburgh, PA, DMA.

part that approximately the same number of TV stations sell in the reverse auction under naive and strategic bidding, averaging across simulation draws to 185.02 under naive bidding and the 84 MHz clearing target and averaging across payout-unique equilibria and simulation draws to 190.35 under strategic bidding. Under the 126 MHz clearing target, the average number of TV stations that sell is 457.64 under naive bidding and 466.23 under strategic bidding. While we thus do not find a sizable distortion in the set of TV stations that relinquish their licenses in the reverse auction, there is of course a substantial transfer from the government—and ultimately taxpayers—to TV stations. There is furthermore a risk that strategic bidding by multi-license owners causes a stage of the incentive auction to fail, leading to a reduction of the clearing target and thus the amount of spectrum that is re-purposed in the incentive auction. As the forward auction is outside of the scope of this paper, we cannot further quantify this risk.

Bidding behavior. The results so far highlight the payout implications of strategic supply reduction. They do not, however, speak to the changes in behavior that underpin these gains. Investigating how different the behavior under strategic bidding is from that under naive bidding is difficult because many TV stations do not sell, regardless of whether they bid truthfully $b_j = s_j$ or overbid $b_j = 900$. Hence, simply counting the number of withheld TV stations in a given equilibrium is not a meaningful measure of differences in behavior. We therefore say that a TV station is essential to a payout-unique equilibrium if and only if that TV station overbids $b_j = 900$ in all equilibria underlying that payout-unique equilibrium. If a TV station is not essential, then there are some underlying equilibria where the TV station is withheld and some where it is not, and yet the payouts to all TV stations remain the same.

Of the 1,670 auction-eligible TV stations, 344 belong to a chain within the same DMA and can thus be part of a supply reduction strategy. Table 12 shows that in comparison, the number of essential TV stations is small, even for the payout-unique equilibria with the most essential TV stations. On average across payout-unique equilibria and simulation draws, there are 26.11 and 38.04 essential TV stations under the 84 MHz and 126 MHz clearing targets. Thus, withholding even a few TV stations from the reverse auction suffices to give rise to equilibria that have significantly higher payouts than those under naive bidding. In this sense, the outcome to the reverse auction is sensitive to small changes in bidding behavior.

Private equity firms. The private equity firms acquired TV stations that frequently set the price for other TV stations in the reserve auction. The private equity firms own 48 or 2.87% of the 1,670 auction-eligible TV stations. Under naive bidding and the 84 MHz clearing target, on average across simulation draws, their TV stations set the price for 15.34 other TV stations, or for 9.55% of all frozen TV stations. As we document in Section 5.2, the private equity firms acquired TV stations with relatively high broadcast volumes, interference free populations, and interference counts. The unexpectedly large number of freezes may therefore reflect station characteristics. We investigate this possibility by regressing the average number of freezes at the station-level on flexible polynomial expansions of the TV station's broadcast volume and interference free population, along with an indicator for whether the TV station is owned by a private equity firm. Even after controlling for station characteristics, the private equity firms own TV stations that are responsible for an additional 0.22 freezes over the average TV station, a sizable effect amounting to 1.13 standard deviations in the number of freezes.

We also find that the private equity firms we study were likely to acquire essential licenses that were pivotal in changing equilibrium payouts. Ranking licenses descendingly by the frequency with which they are essential to a payout-unique equilibrium under the 84 MHz clearing target, we find that the private equity firms, in particular NRJ and OTA, own thirteen of the top 20 licenses. These amount to 26.7% and 39.1% of the overall license holdings of NRJ and OTA.

Not surprisingly, the private equity firms benefit significantly from the reverse auction. As described in Section 5.2, the private equity firms relinquished only 19 TV stations, or 40% of the acquired TV stations, in the reverse auction. Specifically, NRJ relinquishes 2 TV stations, NRJ 7 TV stations, and OTA 10 TV stations. As Table 13 shows, we estimate the private equity firms to relinquish 18.63 TV stations under naive bidding on average across simulation draws and 18.48 TV stations under strategic bidding on average across payout-unique equilibria and simulation draws. Table 13 also shows that the private equity firms experience sizable payout increases from strategic bidding, ranging from 5.5% to 25.3% across firms.

Model fit. We use the available data on the TV stations that relinquished their licenses in the reverse auction to investigate the ability of our model to predict the outcome of the actual reverse auction (see Section 2). Our model correctly predicts a DMA as either having a positive payout or a zero payout with a probability of 0.86 on average across simulation draws under the 84 MHz clearing target and either naive or strategic bidding. This "hit rate" can be decomposed into a probability of 0.80 that we predict a DMA to have a positive payout conditional on the DMA actually having a positive payout in the reverse auction and a probability of 0.88 that we predict a DMA to have a zero payout conditional on the DMA actually having a zero payout. To put

Table 13: Private equity firms' payouts and sales of TV stations, 84 MHz clearing target

	Naive bidding		Strategic bidding		Payout
	Number TV stations sold	Payout ($ million)	Number TV stations sold	Payout ($ million)	increase at mean (%)
LocusPoint	3.04	22.942	3.35	27.657	7.2
	(1.14)	(11.513)	(1.07)	(12.425)	
NRJ	6.10	123.063	6.00	158.012	25.3
	(1.76)	(54.251)	(1.64)	(65.111)	
OTA	9.49	50.867	9.13	59.708	5.5
	(2.11)	(15.926)	(2.04)	(19.080)	

Notes: Payout increase due to strategic bidding calculated as difference between mean payouts under strategic and naive bidding. Using $N^S = 50$ simulation draws for Pittsburgh, PA, DMA.

these probabilities in perspective, randomly drawing 163 TV stations (the actual number of UHF stations that relinquished their licenses) along with their DMAS yields a hit rate of 0.56.

Turning from DMAs to the TV stations themselves, we correctly predict a TV station as either selling or not selling under the 84 MHz clearing target and naive bidding with a probability of 0.884 on average across simulation draws. By comparison, randomly drawing 163 out of 1,670 auction-eligible TV stations yields a hit rate of 0.825.

While this suggests that our model has some ability to predict the outcome of the actual reverse auction, we remind the reader that the noise in our estimated reservation values is large (see Section 6.1), thereby limiting the predictive ability of our model. For example, whereas our model predicts higher payouts in the Los Angeles, CA, DMA than in the New York, NY, DMA under either naive or strategic bidding (see Table 11), payouts in the actual reverse auction were highest in the New York, NY, DMA, followed by the Los Angeles, CA, and Philadelphia, PA, DMAs.[71]

8 Auction design

We illustrate the usefulness of our framework for assessing the design of the reverse auction—and potential modifications to it—in a number of ways. First, we propose a simple change in the auction rules and investigate how placing a restriction on the bids of multi-license owners akin to an activity rule affects their ability to exploit the joint ownership of TV stations. Second, we investigate the consequences of a particular design choice that the FCC made regarding the allowable levels of

[71] As discussed in Section 6.1, we estimate the reservation value of the flagship CBS affiliate on the West Coast, KCBS-TV (facility ID 9628) in the Los Angeles, CA, DMA, to be an order of magnitude larger than its dropout point in the actual reverse auction. In particular, it remained in the auction until a price of $205 million while our estimated reservation value, on average across simulation draws, is $3,293 million. We furthermore estimate the reservation values of two PBS affiliates in the New York, NY, DMA to be an order of magnitude smaller than their dropout points: WNET (facility ID 38336) withdrew from the auction at a price of $547 while the estimated reservation value is $33 million and WEDW (facility ID 13594) withdrew at a price of $425 million while the estimated reservation value is $28 million.

Table 14: Payouts to TV stations nationwide under restriction on multi-license owners

Payouts ($ billion)	Naive bidding	Strategic bidding Mean	Min	Median	Max	Payout increase at mean (%)
Panel A: 126 MHz clearing target						
Nationwide (202 DMAs)	15.767	16.495	16.495	16.495	16.495	4.6
	(2.639)	(2.816)	(2.816)	(2.816)	(2.816)	
Panel B: 84 MHz clearing target						
Nationwide (202 DMAs)	2.477	2.575	2.553	2.575	2.595	3.9
	(0.361)	(0.384)	(0.385)	(0.384)	(0.386)	

Notes: Payout increase at mean calculated as percent difference between mean payouts under strategic and naive bidding. Using $N^S = 50$ simulation draws for Pittsburgh, PA, DMA under 84 MHz clearing target.

interference between TV stations. Third, we use our framework to investigate the efficiency of the reverse auction and to gauge the potential efficiency gains from alternative designs.

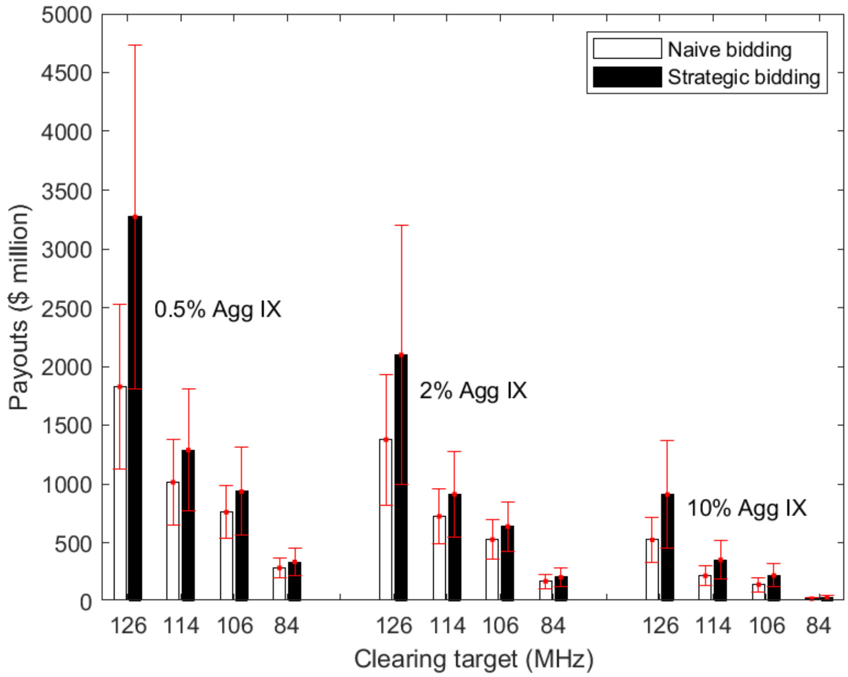
8.1 Restriction on multi-license owners

We have so far shown that strategic supply reduction leads to a substantial transfer from the government to TV stations. To highlight how our model can be used in designing future auctions, we consider a simple change in the auction rules that mitigates the payout increase from strategic bidding. In particular, we investigate how a restriction on the bids of multi-license owners affects their ability to exploit the joint ownership of TV stations.

Example 1 in Section 3.1 suggests that strategic supply reduction is more likely to be profitable if the increase in the base clock price from withholding a TV station can be leveraged by selling another TV station with high broadcast volume. To weaken this mechanism, we stipulate that to withhold a TV station with a lower broadcast volume, a multi-license owner must also withhold any other TV station with a higher broadcast volume. This restriction exploits the fact that broadcast volume is observable and contractible, in the spirit of the literature on regulation (Laffont and Tirole, 1986). However, we set aside legal considerations the FCC may face in implementing a similar rule change.

Table 14 shows how the rule change affects our main results in Table 9. The payout increase from strategic bidding is between 71% and 89% less than in Table 9, depending on the clearing target. The rule change mitigates payout increases by requiring that multi-license owners first withdraw TV stations with higher broadcast volumes that likely also have higher reservation values. Our estimates imply that, on average across simulation draws, the correlation between broadcast volume and reservation value is 0.39 for the 1,670 auction-eligible TV stations. Interestingly, the rule change also renders the second equilibrium discussed in Section 7.1 for the Philadelphia, PA, DMA infeasible, since there both multi-license owners withhold the TV station with the lower broadcast volume from the reverse auction.

Figure 5: Payouts to TV stations in Philadelphia, PA, DMA under alternative interference levels and clearing targets



8.2 Relaxing repacking constraints

In designing the reverse auction, the FCC had to make a number of choices. One such choice was the maximum loss in population served that a TV station may suffer in the repacking process, as discussed in Section 4.2. While the FCC settled on a 0.5% interference level, the alternative, looser standards of 2% and 10% would have eliminated some interference constraints on the repacking process and thus made TV stations more substitutable.

To understand the role of the interference level and the implied degree of substitutability, we simulate the reverse auction for the Philadelphia, PA, DMA under 12 different scenarios. Each scenario pairs one of the three interference levels (0.5%, 2%, and 10%) with one of the four clearing targets (126 MHz, 114 MHz, 106 MHz, and 84 MHz) that the FCC considered. Under these three interference levels, the average number of interference constraints for a TV station in the Philadelphia, PA, DMA drops from 62.96 for the 0.5% interference level to 48.88 and 32.63 for the 2% and 10% interference levels, respectively. The results are shown in Figure 5, where we display payouts (in $ million) under naive bidding as white bars and payouts under strategic bidding as black bars, with 95% confidence intervals in red.

There are a few conclusions to draw from Figure 5. First, in line with the nationwide results in Table 9, payouts increase in the clearing target, irrespective of the form of bidding and the interference level. Second, also as in the nationwide results, the scope for strategic supply reduction, as measured by the payout increase from strategic bidding, increases in the clearing target. Third, payouts decrease in the interference level, as does the scope for strategic supply reduction. As TV stations become more substitutable in the repacking process, in the extreme it is unlikely that withholding a TV station from the reverse auction has a large effect on payouts.

Strategic supply reduction has been explored in previous work on multi-unit auctions in wholesale electricity markets (e.g., Wolfram, 1998, Hortacsu and Puller, 2008). Borenstein, Bushnell and Wolak (2002) note that the effect of such an exercise of market power can be large when demand or supply is inelastic. In contrast to electricity, TV stations are not homogeneous in the repacking process because of interference constraints. We show that product differentiation amplifies the impact of strategic supply reduction, even though the FCC's demand for TV stations is elastic. Our results thus complement the earlier literature by highlighting the interaction of product differentiation and strategic supply reduction.

8.3 Efficiency

In Section 7.2, we have shown that although strategic bidding by multi-license owners causes a substantial transfer from the government to TV stations in the reverse auction, it does not entail large efficiency losses relative to naive bidding. In Sections 8.1 and 8.2, we have also shown that the transfer from the government to TV stations can be greatly reduced by relatively simple changes in the design of the reverse auction. We now ask if re-designing the reverse auction has the potential to improve efficiency. To answer this question, rather than trying out alternative designs for the reverse auction or modeling altogether different mechanisms such as bilateral negotiations between the government and TV stations, we show that the reverse auction comes close to being efficient. Thus, the scope for further efficiency gains is limited.

We say that an outcome is efficient if it meets the clearing target and minimizes the total reservation value of acquired TV stations or, equivalently, if it meets the clearing target and maximizes the total reservation value of TV stations that remain on the air. To obtain the efficient outcome, we follow Newman et al. (2017) and solve the binary programming problem detailed in Appendix E. We compare the efficient outcome to the outcome of the reverse auction under naive bidding in terms of TV stations that go off the air and compute the value loss ratio, defined as the total reservation value of acquired TV stations in the reverse auction relative to the efficient outcome. We take the regional approach described in Section 6.2 by restricting the binary programming problem to a repacking region. Similar to Newman et al. (2017) in their analysis of New York, NY, we compute the value loss ratio considering all TV stations in the repacking region.[72]

Table 15 shows the value loss ratio, averaged across simulation draws, for select DMAs for the 84 MHz and 126 MHz clearing targets. We conduct the analysis for the top ten DMAs in terms

[72] Restricting the computation of the value loss ratio to the TV stations in the focal DMA causes excess volatility and skewness for two reasons. First, as the binary programming problem considers all TV stations in the repacking region, the value loss ratio is no longer bounded below by one. Second, the value loss ratio becomes infinite if the efficient outcome does not entail acquiring any TV station in the focal DMA. As a result, the value loss ratio restricted to the TV stations in the focal DMA can be larger than what we report below.

Table 15: Value loss ratio for top ten DMAs

DMA	Payout rank	Clearing target 84 MHz	Clearing target 126 MHz
New York, NY	1	1.11	1.05
Los Angeles, CA	2	1.05	1.07
Philadelphia, PA	3	1.08	1.04
San Francisco, CA	4	1.06	1.05
Boston, MA	5	1.15	1.11
Washington, DC	6	1.09	1.04
Chicago, IL	7	1.11	1.07
Milwaukee, WI	8	1.11	1.06
Hartford, CT	9	1.08	1.04
Providence, RI	10	1.08	1.04

Notes: Using $N^S = 98$ simulation draws for the New York, NY, DMA and 84 MHz clearing target, as CPLEX did not solve the binary programming problem for the remaining draws within one month with 32 CPUs.

of payouts in the reverse auction.[73] This set includes seven out of the ten largest DMAs, as well as Milwaukee, WI, Hartford-New Haven, CT, and Providence, RI-New Bedford, MA. The value loss ratios are between 1.05 and 1.15 for the 84 MHz clearing target and between 1.04 and 1.11 for the 126 MHz clearing target. By comparison, Newman et al. (2017) restrict attention to 218 TV stations in a neighborhood of New York, NY, and the 126 MHz clearing target and report a value loss ratio of 1.05. Overall, the potential efficiency gains from re-designing the reverse auction appear to be limited.

9 Extensions

As discussed in Section 2, payouts in the actual reverse auction amounted to \$10.1 billion at the 84 MHz clearing target. Conservatively assuming full participation and a limited geographic extent of strategic bidding, we predict payouts of \$2.812 billion on average across payout-unique equilibria and simulation draws. Similarly, TV stations demanded payouts of \$86.4 billion at the initial clearing target of 126 MHz in stage 1 of the actual reverse auction, compared to our prediction of \$22.457 billion. In this section, we investigate the sensitivity of our main results to these two assumptions.

9.1 Reduced participation

In our ex-ante analysis of the reverse auction, we conservatively assumed full participation of the 1,670 auction-eligible TV stations. As described in Section 6.2, the FCC has long been concerned about participation. Klemperer (2016) and Milgrom and Segal (2020) similarly point to participation as a primary concern for auction design. While the FCC had initially decided not to release

[73] To give a sense of the computational burden, the analysis took a total of roughly 13,000 CPU-days.

Table 16: Payouts to TV stations nationwide under realized participation

Payouts ($ billion)	Naive bidding	Strategic bidding				Payout increase at mean (%)
		Mean	Min	Median	Max	
Panel A: 84 MHz clearing target						
Nationwide (202 DMAs)	4.337	4.760	4.561	4.746	4.986	9.8
	(0.713)	(0.755)	(0.729)	(0.754)	(0.839)	

Notes: Payout increase at mean calculated as percent difference between mean payouts under strategic and naive bidding. Using $N^S = 50$ simulation draws for Pittsburgh, PA, DMA under 84 MHz clearing target.

data on participation or bids in the reverse auction, it has subsequently reversed course. This allows us to examine the sensitivity of our main results to the realized level of participation.

The recently released data on participation and bids shows that only 898, or 53.77%, of the 1,670 auction-eligible TV stations participated in the reverse auction. Contrary to the FCC's expectations of low participation by sentimental owners, participation was higher among independently-owned TV stations than those held by multi-license owners: 63.58% of independently owned TV stations participated, compared to only 52.66% of TV stations held by multi-license owners, consistent with strategic behavior by multi-license owners.

We use the participation data to refine our simulation exercise by setting the bid of a non-participating TV station to $b_j = 900$. Table 16 shows the resulting payouts to TV stations under naive and strategic bidding and the 84 MHz clearing target.[74] Comparing Table 16 to our main results in Table 9 highlights the importance of participation for the success of the reverse auction as payouts to TV stations increase significantly under realized participation. On average across payout-unique equilibria and simulation draws, payouts amount to $4.760 billion under strategic bidding and realized participation compared to $2.812 billion under full participation, an increase of nearly 70%.

One likely reason why many TV stations may choose to remain on the air is the must-carry provision of the Cable Television Consumer Protection and Competition Act of 1992 (see Section 6.1), which greatly broadens their reach and potential advertising audience. One simple measure to increase participation, therefore, would be to allow TV stations to relinquish their licenses but retain their must-carry status, so that they can continue to operate as businesses and reach viewers through cable systems.

[74]With fewer participating TV stations, the reverse auction is more likely to fail at the outset (see footnote 28). As described in Section 6.2, we discard equilibria that entail a failure at the outset. In 0.04% of runs of the reverse auction, there is no pure strategy equilibrium under strategic bidding and the 84 MHz clearing target and we revert to naive bidding. The reverse auction does not fail at the outset under naive bidding and the 84 MHz clearing target. We do not repeat the exercise for the 126 MHz clearing target because failure at the outset becomes pervasive.

9.2 Multi-market strategies

Strategic bidding may extend beyond market boundaries if multi-license owners withhold a TV station in a DMA from the reverse auction to drive up the freezing base clock price for another TV station they own in a neighboring DMA. As we document in Section 5.1, cross-market multi-license ownership is pronounced. We illustrate how multi-market strategies may work, continuing with the Philadelphia, PA, DMA as a case study in the interest of computational tractability.

The 24 TV stations in the Philadelphia, PA, DMA are held by 18 owners. 12 of these owners hold at least one additional license in the repacking region but outside the Philadelphia, PA, DMA. Abandoning the restriction from Section 6.2 that any TV station outside the focal DMA bids truthfully increases the number of strategy profiles from 729 to 8.80 trillion. As this is computationally infeasible, we focus on one of the 12 owners that hold at least one additional license in the repacking region, namely NRJ. This increases the number of strategy profiles from 729 to 1701.

In late 2012, NRJ purchased WGCB-TV (facility ID 55350) in the Harrisburg, PA, DMA for $9 million. WGCB-TV is located in Red Lion, PA, towards both the Philadelphia, PA, and Baltimore, MD, DMAs. While NRJ owns no other TV station in the Harrisburg, PA, DMA, it had previously purchased WTVE and WPHY-CD (facility IDs 55305 and 74464) in the Philadelphia, PA, DMA in late 2011 and early 2012 for $30.4 million and $3.5 million, respectively. Figure 6 shows the overlap between the service contours of WGCB-TV (in red), WTVE (in blue), and WPHY-CD (in yellow).[75] WGCB-TV has a very high interference count and may interfere with 161 TV stations in the repacking process. Hence, if NRJ withholds WGCB-TV from the reverse auction, this may affect prices in the Philadelphia, PA, DMA and potentially other DMAs as well; alternatively, withholding a TV station in the Philadelphia, PA, DMA may increase the payout to WGCB-TV.

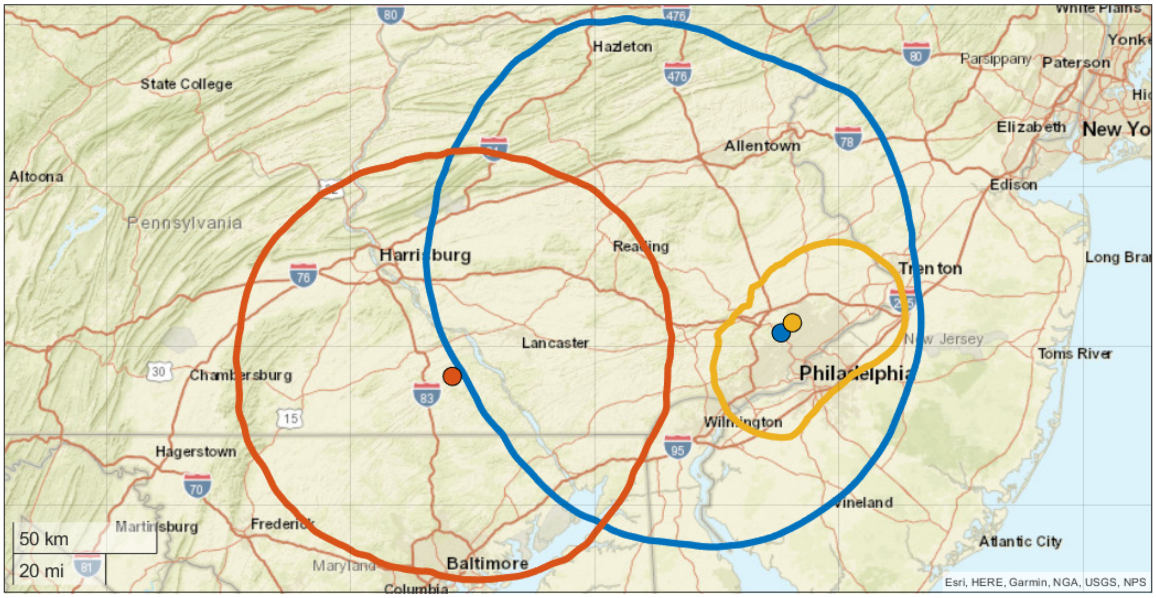
To investigate, we allow NRJ to bid strategically on WGCB-TV in concert with its TV stations in the Philadelphia, PA, DMA. Table 17 compares payouts to TV stations in the Philadelphia, PA, DMA under the multi-market strategy to payouts in our base case. Payouts increase under the multi-market strategy under both the 126 MHz and the 84 MHz clearing target, as do the gains from strategic bidding. The fact that accounting for a single case of cross-market multi-license ownership has a discernible impact suggests that accounting for all such cases—if it were computationally feasible—potentially has a dramatic impact on payouts in the reverse auction.

10 Conclusions

In this paper, we explore the implications of ownership concentration for the recently-concluded incentive auction that re-purposed spectrum from broadcast TV to mobile broadband usage. Ownership concentration is a policy concern as the FCC has welcomed the acquisitions of TV stations by private equity firms and other outside investors in the run-up to the incentive auction. The FCC worried about encouraging a healthy supply of TV stations in the reverse auction and viewed out-

[75] We obtain service contours from the FCC's TV Query Broadcast Station Search at https://www.fcc.gov/media/television/tv-query, accessed on March 15, 2018.

Figure 6: Service contours of WGCB-TV, WTVE, and WPHY-CD



Notes: Dots denote facility locations. The red dot denotes WGCB-TV in the Harrisburg, PA, DMA. The blue dot denotes WTVE and the yellow dot denotes WPHY-CD in the Philadelphia, PA, DMA.

Table 17: Payouts to TV stations in Philadelphia, PA, DMA under multi-market strategy

Payouts ($ billion)	Naive bidding	Strategic bidding Mean	Min	Median	Max	Payout increase at mean (%)
Panel A: 126 MHz clearing target						
Base case	1.826	3.273	2.783	3.222	3.818	79.2
	(0.702)	(1.461)	(1.558)	(1.531)	(1.768)	
Multi-market strategy	1.826	3.431	2.829	3.449	4.039	87.9
	(0.702)	(1.482)	(1.533)	(1.567)	(1.811)	
Panel B: 84 MHz clearing target						
Base case	0.285	0.336	0.317	0.333	0.358	17.9
	(0.085)	(0.116)	(0.109)	(0.120)	(0.137)	
Multi-market strategy	0.285	0.357	0.335	0.352	0.384	25.3
	(0.085)	(0.120)	(0.117)	(0.118)	(0.146)	

Notes: Payouts under multi-market strategy exclude WGCB-TV for comparability to base case. Payout increase at mean calculated as percent difference between mean payouts under strategic and naive bidding.

side investors as more likely to part with their TV stations than potentially "sentimental" owners.[76] At the same time, as our paper shows, ownership concentration is likely to give rise to strategic supply reduction.

Using a large-scale valuation exercise to estimate reservation values for the auction-eligible TV stations, we compare the outcome of the reverse auction under strategic bidding when we account for the ownership pattern in the data with the outcome under naive bidding. We show that strategic supply reduction has a large impact on prices and payouts to TV stations. For the 126 MHz clearing target, strategic bidding by multi-license owners increases nationwide payouts by 42.4% on average; for the 84 MHz clearing target, strategic bidding increases nationwide payouts by 13.5%.

Our simulation exercise affords several additional conclusions. First, while single-license owners do not themselves engage in strategic supply reduction, as a group they witness payout increases that are almost as large as those seen by multi-license owners. Second, there is significant heterogeneity in payouts as well as in payout increases due to strategic bidding across DMAs. Third, strategic supply reduction has limited efficiency implications. Fourth, the outcome of the reverse auction is sensitive to small changes in bidding behavior in that withholding even a few TV stations suffices to give rise to equilibria that have significantly higher payouts than those under naive bidding.

Our main results are likely to understate the impact of strategic supply reduction on prices and payouts to TV stations because we make several conservative assumptions. We show that allowing strategic bidding to extend beyond market boundaries has the potential to further exacerbate payout increases. Perhaps even more important, we show that moving from our baseline assumption of full participation to reduced participation substantially increases both naive payouts and the gains from strategic bidding.

Our paper differs from most of the empirical literature on auctions and market design by taking an ex ante perspective. We illustrate the usefulness of this approach in three ways. First, we propose a simple change in the auction rules and investigate how placing a restriction on the bids of multi-license owners affects their ability to exploit the joint ownership of TV stations. Second, we trace out the relationship between the interference level that the FCC chooses—and the implied degree of substitutability between TV stations in the repacking process—and payouts in the reverse auction. Third, we investigate the efficiency of the reverse auction. We hope that the framework we provide proves useful in designing future auctions geared at re-purposing spectrum toward more efficient uses.

[76] See "FCC Makes Pitch for TV Stations' Spectrum", The Wall Street Journal, October 1, 2014.

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Appendix

A Data sources

In this appendix, we discuss several details of the data sources we rely on and describe how we construct our sample and primary variables.

A.1 TV stations

We restrict attention to TV stations located in the U.S. excluding Puerto Rico and the Virgin Islands that the FCC has declared as eligible for the reverse auction. Table A1 breaks down these 2,150 TV stations by type of service, type of use, and power output.

Table A1: TV station counts by type of service, type of use, and power output

		Full-power		Low-power	
		Primary	Satellite	Class-A	Total
UHF	Commercial	944	59	378	1,670
	Non-commercial	282	0	7	
VHF	Commercial	293	57	24	480
	Non-commercial	105	0	1	
Total		1,740		410	2,150

A.2 DMAs

DMAs are ranked annually according to market size as measured by the number of homes with at least one television (henceforth, TV households, measured in thousand). Table A2 lists the top ten DMAs in 2015 along with some characteristics from the BIA data. DMA population is measured as number of people (in million) as opposed to number of TV households. Income is average per capita disposable personal income (in \$). The number of TV station covers the 2,150 TV stations located in the U.S. excluding Puerto Rico and the Virgin Islands that the FCC has declared as eligible for the reverse auction.

A.3 BIA data

After restricting to full-power stations (primary and satellite stations) and low-power class-A and LPTV stations, the BIA data provides us with 66,078 station-year observations from 2003 to 2013 and for 2015. Commercial stations make up 56,856 observations and non-commercial stations, including dark stations, 9,222 observations.

The BIA data provides station, owner and market characteristics, as well as transaction histories covering the eight most recent changes in the ownership of a TV station. Advertising revenue and DMA rank are provided for each year from 2003 to 2013 and for 2015. DMA population is provided

Table A2: Top ten DMAs in 2015

Rank	DMA	TV households (thousand)	DMA population (million)	Income ($)	TV stations
1	New York, NY	7,368	21.4	57,769	28
2	Los Angeles, CA	5,490	16.3	44,678	32
3	Chicago, IL	3,475	9.8	46,976	24
4	Philadelphia, PA	2,918	8.1	48,620	28
5	Dallas Fort Worth, TX	2,646	7.7	44,590	21
6	San Francisco, CA	2,485	7.3	64,442	26
7	Washington, DC	2,444	6.9	56,362	20
8	Boston, MA	2,411	6.5	56,463	23
9	Atlanta, GA	2,386	6.8	38,275	19
10	Houston, TX	2,374	6.9	49,255	19

for 2007, 2008, 2012, 2013, and 2015. We use the data for 2007 and 2008 to extrapolate DMA population linearly to earlier years and the data for 2008 and 2013 to interpolate linearly to the years in-between. With few exceptions, other characteristics are provided only for 2012 and for 2015.[77] Transaction histories are provided from 2003 to 2013.

For commercial full-power and class-A stations, advertising revenue is missing for 4,892, or 24.9%, station-year observations. Table A3 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 their advertising revenues into those of their parent primary stations.[78] Missing values are further concentrated among low-power class-A stations. Given this prevalence, we supplement the sample with data on 1,331 low-power LPTV stations with non-missing revenue data. LPTV stations are not auction-eligible, but are more comparable to class-A stations than full-power stations. The bottom panel of Table A3 summarizes the prevalence of missing revenue data by affiliation, focusing only on full-power and class-A stations. Revenue data is more frequently unavailable for Spanish-language networks (Azteca America, Independent Spanish, Telemundo, Unimas, and Univision), other minor networks, and independent stations. There are no discernible patterns in missing values along other dimensions of the data such as market size.

We impute missing advertising revenue as follows. For primary stations, we regress 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 for 2015. We include in X_{jt} as station characteristics the log of the interference free population coverage (in thousand) of the TV station, an indicator for whether the TV station has multicast sub-channels, an indicator for

[77] An "on air date" is provided and we drop observations for a TV station before it went on the air. A previous affiliation and the date of the affiliation change are provided. We manually fill in historical affiliations, including the merger of United Paramount and Warner Bros in 2006 to form CW and the creation of MyNetwork TV in 2006.

[78] We enforce this convention for the 84 station-year observations where a satellite station has non-missing advertising revenue. We manually link the 116 satellite stations in Table A1 to 78 primary stations because BIA does not provide this information.

low-power LPTV stations, an indicator for full-power stations, fixed effects for the eleven network affiliations in Table A3, fixed effects for the interaction of affiliation groups (see Appendix C.1.1) with U.S. states, as owner characteristics an indicator for whether the owner owns more than one TV station in the same DMA, ownership category fixed effects (whether the owner owns between two and ten, or more than ten TV stations across DMAs), and as DMA characteristics 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 Appendix C.1.1), and the log of DMA population (in thousand). The adjusted R^2 is 0.99 in all years, suggesting that we capture most of the variation in advertising revenue across TV stations and years. We report the parameter estimates in Online Appendix F.

With the parameter estimates in hand, we impute advertising revenue AD_{jt} for primary stations, where missing, 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 $\hat{\sigma}^2$. Where applicable, we then allocate revenue between the primary station and any affiliated satellite stations in proportion to their interference free population.

Table A3: Missing advertising revenue for commercial stations

		Missing advertising revenue	
	Station-year obs.	Station-year obs.	%
Full-power			
Primary	14,698	967	6.58
Satellite	1,411	1,327	94.05
Low-power			
Class-A	4,967	3,925	79.02
LPTV	37,191	35,860	96.42
Major networks			
ABC	2,690	433	16.10
CBS	2,640	339	12.84
Fox	2,471	344	13.92
NBC	2,664	403	15.13
Minor networks			
CW	950	112	11.79
MyNetwork TV	833	146	17.53
United Paramount	269	37	13.75
Warner Bros	269	26	9.67
Spanish-language networks	1,911	608	31.82
Other	3,225	1,631	50.57
Independent	3,133	2,140	68.31

A.4 NAB data

NAB collects financial information on cash flow, revenue, and expenses broken down into detailed source categories for commercial full-power stations. We define advertising revenue as the sum of local, regional, national, and political advertising revenue, commissions, and network compensation. We further define non-broadcast revenue as the sum of total trade-outs and barter, multicast revenue, and other broadcast related revenue. Finally, we define fixed cost as the sum of engineering expenses and general and administrative expenses.

NAB reports the data at various levels of aggregation. Table A4 shows the resulting 66 tables in 2012.[79] The number of tables fluctuates slightly year-by-year because NAB imposes a minimum of ten TV stations per aggregation category to ensure confidentiality.[80,81] Note that a TV station may feature in more than one table. For example, WABC-TV (facility ID 1328), the New York ABC affiliate, 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 as well as the first, second, and third quartile for cash flow and the detailed source categories for revenue and expenses. Because we do not observe correlations between the categories, we can construct the mean of advertising revenue, non-broadcast revenue, and fixed cost but not the quartiles. We present a sample of the NAB data for select aggregation categories in Table A5.

To validate the data, first 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 0.980. Next, to investigate the consequences of imputing advertising revenue, where missing, in the BIA data, we equally split the sample into two groups based on the amount of imputation. For each of the 662 NAB tables, we calculate the share of stations in the BIA data that qualify for the table and have imputed advertising revenue. The 331 pairs of means with below-median amounts of imputation exhibit a correlation of 0.980 and the 331 pairs of means with above-median amounts of imputation exhibit a correlation of 0.975. This suggests that imputing advertising revenue does not significantly diminish the validity of the BIA data.

B Additional proposition and proofs

In this appendix, we first state Proposition 2. Then we prove Propositions 1 and 2.

Proposition 2 tackles the case of underbidding and parallels Proposition 1:

[79] We exclude 15 aggregation categories that are defined by total revenue because the BIA data is restricted to advertising revenue.

[80] In 2012, NAB received 785 responses to 1,288 questionnaires, a response rate of 60.9%.

[81] 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 the cash flow estimation in Section C.1.2.

Proposition 2. *Suppose firm i owns multiple TV stations including TV station j, i.e., $|J_i| > 1$ and $j \in J_i$. Consider a vector of bids b with $0 < b_j < s_j$. If $\pi_i(b_j, b_{-j}) > \pi_i(s_j, b_{-j})$, then $\pi_i(0, b_{-j}) \geq \pi_i(b_j, b_{-j})$.*

Turning to the proofs, we first state and prove two lemmas characterizing the impact of b_j on the payout to TV station j and on the profit of its owner, firm i. In a slight abuse of notation, we partition the vector $b = (b_1, \ldots, b_N)$ of bids as (b_i, b_{-i}), where b_i is the vector of bids of firm i and b_{-i} is the vector of bids of the other firms, and as (b_j, b_{-j}), where b_j is the bid of TV station j and b_{-j} is the vector of bids of the other TV stations. Let $\tau(j) \geq 1$ denote the round of the reverse auction where TV station j first opts to remain on the air (unless it has already been frozen), i.e., $P_{\tau(j)-1} > b_j \geq P_{\tau(j)}$ (and we set $P_0 = \infty$). Partition the set of frozen TV stations at the conclusion of the reverse auction as $F^*(b) = \bigcup_{j \in \{1,\ldots,N\}} F_j^*(b)$, where $F_j^*(b) \subseteq \{1, ..., N\}$ is the (possibly empty) set of TV stations that are frozen by TV station j given the vector of bids b.[82] Note that TV station j determines the payout $PO_k(b) = P_{\tau(j)}\varphi_k$ to all TV stations $k \in F_j^*(b)$. Finally, denote the set of inactive TV stations at the conclusion of the reverse auction as $I^*(b)$.

Lemma 3. *If $j \in J_i$ and $j \in F^*(b)$, then $\pi_i(b) = \pi_i(\tilde{b}_j, b_{-j})$ for all $\tilde{b}_j \leq b_j$.*

Proof. Because $j \in F^*(b)$, it must be that $j \in F_l^*(b)$ for some TV station l with $b_l > b_j$, i.e., TV station l freezes TV station j under the vector of bids b. Note that $j \in F_l^*(\tilde{b}_j, b_{-j})$ for all $\tilde{b}_j \leq b_j$ and thus $F_j^*(b) = F_j^*(\tilde{b}_j, b_{-j}) = \emptyset$, i.e., TV station l continues to freeze TV station j under the vector of bids $(\tilde{b}_j, b_{-j})$ and TV station j does not freeze another TV station. Hence, we have to show that

$$\pi_i(b) = \sum_{k \neq j} \sum_{m \in J_i \cap F_k^*(b)} (P_{\tau(k)}\varphi_m - v_m) = \sum_{k \neq j} \sum_{m \in J_i \cap F_k^*(\tilde{b}_j, b_{-j})} (P_{\tau(k)}\varphi_m - v_m) = \pi_i(\tilde{b}_j, b_{-j})$$

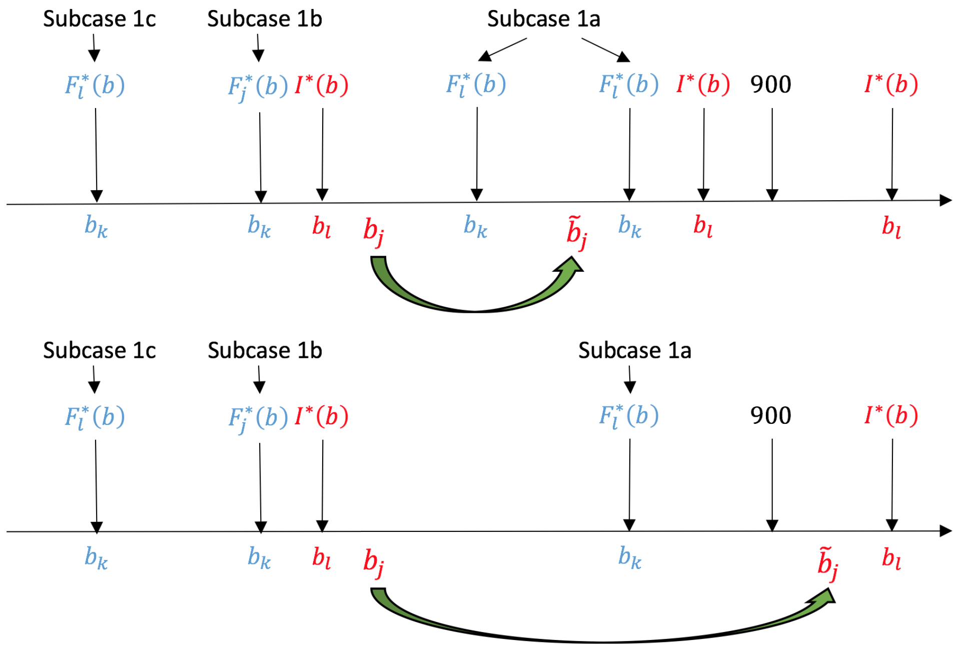
for all $\tilde{b}_j \leq b_j$. It suffices to show that $F_k^*(b) = F_k^*(\tilde{b}_j, b_{-j})$ for all $\tilde{b}_j \leq b_j$ and $k \neq j$. First consider any TV station k with $b_k > b_j$. It is obvious that $F_k^*(b) = F_k^*(\tilde{b}_j, b_{-j})$ for all $\tilde{b}_j \leq b_j$. Consider next any TV station k with $b_k < b_j$. Because $F_{\tau(l)+1}(b) = F_{\tau(l)+1}(\tilde{b}_j, b_{-j})$ and $A_{\tau(l)+1}(b) = A_{\tau(l)+1}(\tilde{b}_j, b_{-j})$, the reverse auction progresses the same from round $\tau(l) + 1$ on under the vector of bids b as under the vector of bids $(\tilde{b}_j, b_{-j})$. Hence, $F_k^*(b) = F_k^*(\tilde{b}_j, b_{-j})$ for all $\tilde{b}_j \leq b_j$. This completes the proof. □

Lemma 4. *If $j \in I^*(b)$ and $S(Y_1(b) \cup \{j\}, R) = 1$, then $F^*(b) = F^*(\tilde{b}_j, b_{-j})$ and $PO_k(b) \leq PO_k(\tilde{b}_j, b_{-j})$ for all $\tilde{b}_j > b_j$ and $k \in \{1, ..., N\}$.*

Proof. The condition $S(Y_1(b) \cup \{j\}, R) = 1$ guarantees that the reverse auction does not fail at the outset for any vector of bids $(\tilde{b}_j, b_{-j})$. Consider first TV station j. Because $j \in I^*(b)$, it must be that $j \in I^*(\tilde{b}_j, b_{-j})$ and thus $PO_j(b) = 0 = PO_j(\tilde{b}_j, b_{-j})$ for all $\tilde{b}_j > b_j$. Next consider any TV

[82] If a TV station $k \in Z_1(b)$ is frozen at the outset of the reverse auction, then we assign it to a TV station $l \in Y_1(b)$ and say that $k \in F_l^*(b)$.

Figure A1: Case 1 and subcases in proof of Lemma 4



station $k \neq j$. If $k \in I^*(b)$, then $k \in I^*(\tilde{b}_j, b_{-j})$ for all $\tilde{b}_j > b_j$ and thus $PO_k(b) = 0 = PO_k(\tilde{b}_j, b_{-j})$. Assuming $k \notin I^*(b)$ and therefore $b_k < 900$, we proceed in two cases, depending on whether or not there exists any inactive TV station with its bid between b_j and $\widetilde{b}_j$.

Case 1: There does not exist any inactive TV station with its bid between b_j and $\widetilde{b}_j$, i.e., $\{l | l \in I^*(b), b_j < b_l < \widetilde{b}_j\} = \emptyset$. Consider a TV station $k \neq j$. Figure A1 illustrates the possible subcases.

Subcase 1a: If $b_j < b_k$, then $k \in F_l^*(b)$ for some TV station l with $b_l \geq \widetilde{b}_j$. Thus $k \in F_l^*(\widetilde{b}_j, b_{-j}) \cup F_1(\widetilde{b}_j, b_{-j})$ and $PO_k(b) = P_{\tau(l)}\varphi_k = PO_k(\widetilde{b}_j, b_{-j})$.

Subcase 1b: If $b_k < b_j$ and $k \in F_j^*(b)$, then $k \in F_j^*(\widetilde{b}_j, b_{-j}) \cup F_1(\widetilde{b}_j, b_{-j})$ and $PO_k(b) = P_{\tau(j)}\varphi_k < PO_k(\widetilde{b}_j, b_{-j})$.

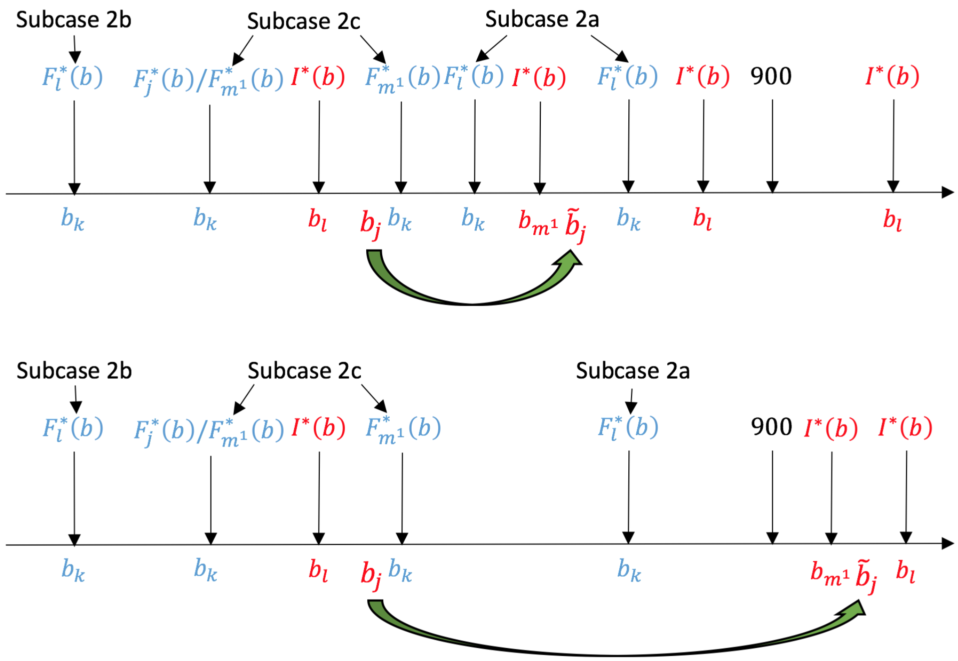
Subcase 1c: If $b_k < b_j$ and $k \in F_l^*(b)$ for some TV station $l \in I^*(b) \setminus \{j\}$, then $k \in F_l^*(\widetilde{b}_j, b_{-j}) \cup F_1(\widetilde{b}_j, b_{-j})$ and thus $PO_k(b) = P_{\tau(l)}\varphi_k = PO_k(\widetilde{b}_j, b_{-j})$.

Case 2: There exists at least one inactive TV station with its bid between b_j and $\widetilde{b}_j$, i.e., $M = \{m | m \in I^*(b), b_j < b_m < \widetilde{b}_j\} \neq \emptyset$. Let $M = \{m^1, ..., m^n\}$ and enumerate its members such that $b_j < b_{m^1} < b_{m^2} < ... < b_{m^n} < \widetilde{b}_j$. It suffices to show that $F^*(b) = F^*(b_{m^1} + \epsilon, b_{-j})$ and $PO_k(b) \leq PO_k(b_{m^1} + \epsilon, b_{-j})$ for all $k \neq j$ and any sufficiently small $\epsilon > 0$; it then follows that $F^*(b) = F^*(b_{m^1} + \epsilon, b_{-j}) = ... = F^*(b_{m^n} + \epsilon, b_{-j}) = F^*(\widetilde{b}_j, b_{-j})$, where the last equality follows from Case 1, and $PO_k(b) \leq PO_k(b_{m^1} + \epsilon, b_{-j}) \leq ... \leq PO_k(b_{m^n} + \epsilon, b_{-j}) \leq PO_k(\widetilde{b}_j, b_{-j})$ for all $k \neq j$ for the same reason.

Consider a TV station $k \neq j$. Figure A2 illustrates the possible subcases.

Subcase 2a: If $k \in F_l^*(b)$ for some TV station l with $b_{m^1} < b_l$, then $k \in F_l^*(b_{m^1} + \epsilon, b_{-j}) \cup F_1(\widetilde{b}_j, b_{-j})$ and $PO_k(b) = P_{\tau(l)}\varphi_k = PO_k(b_{m^1} + \epsilon, b_{-j})$.

Figure A2: Case 2 and subcases in proof of Lemma 4



Subcase 2b: If $k \in F_l^*(b)$ for some TV station l with $b_l < b_j$, then $k \in F_l^*(b_{m^1} + \epsilon, b_{-j})$ and $PO_k(b) = P_{\tau(l)}\varphi_k = PO_k(b_{m^1} + \epsilon, b_{-j})$.

Subcase 2c: If $k \in F_j^*(b) \cup F_{m^1}^*(b)$, then $k \in F_j^*(b_{m^1} + \epsilon, b_{-j}) \cup F_{m^1}^*(b_{m^1} + \epsilon, b_{-j}) \cup F_1(\widetilde{b}_j, b_{-j})$ and $PO_k(b) \leq P_{\tau(m^1)}\varphi_k = PO_k(b_{m^1} + \epsilon, b_{-j})$.

This completes the proof. □

We are now ready to prove Proposition 1:

Proof of Proposition 1. We first show that $j \in I^*(b)$. Suppose to the contrary that $j \notin I^*(b)$. Then $j \in F^*(b)$ and Lemma 3 implies $\pi_i(b) = \pi_i(s_j, b_{-j})$, contradicting $\pi_i(b) > \pi_i(s_j, b_{-j})$. Hence, $j \in I^*(b)$ and it follows from Lemma 4 that

$$\begin{aligned}
\pi_i(b) &= \sum_{l \in J_i \cap F^*(b)} (PO_l(b) - v_l) \\
&\leq \sum_{l \in J_i \cap F^*(900, b_{-j})} (PO_l(900, b_{-j}) - v_l) \\
&= \pi_i(900, b_{-j}).
\end{aligned}$$

□

The proof of Proposition 2 largely parallels that of Proposition 1:

Proof of Proposition 2. Suppose to the contrary that $\pi_i(0, b_{-j}) < \pi_i(b)$. Then it must be that $j \in I^*(b)$; otherwise, $j \in F^*(b)$ and it follows from Lemma 3 that $\pi_i(0, b_{-j}) = \pi_i(b)$. Hence,

$j \in I^*(b)$ and it follows from Lemma 4 that

$$\begin{aligned}\pi_i(b) &= \sum_{l \in J_i \cap F^*(b)} (PO_l(b) - v_l) \\ &\leq \sum_{l \in J_i \cap F^*(s_j, b_{-j})} (PO_l(s_j, b_{-j}) - v_l) \\ &= \pi_i(s_j, b_{-j}),\end{aligned}$$

contradicting $\pi_i(b) > \pi_i(s_j, b_{-j})$. □

C Reservation values

In this appendix, we provide details on how we estimate the reservation value of a TV station going into the reverse auction.

C.1 Cash flows

C.1.1 Functional forms

In the cash flow model in equation (10), we parameterize $\alpha(X_{jt};\beta)$, $RT(X_{jt};\gamma)$, and $F(X_{jt};\delta)$ as functions of station and market characteristics X_{jt} as

$$\begin{aligned}\alpha(X_{jt};\beta) =& \sum_{a=1}^{9} \beta_0^a 1(\mathit{Affiliation}_{jt} = a) + \beta_1 Fox_{jt}(t-2002) \\ &+ \sum_{s=2003}^{2012} \beta_2^s 1(t=s) + \beta_3 CompIndex_{jt} + \beta_4 WealthIndex_{jt}, \\ RT(X_{jt};\gamma) =& \exp\left(\sum_{h=1}^{3} \gamma_0^h 1(\mathit{Group}_{jt} = h) + \gamma_1 \ln(PopServed_{jt}) + \gamma_2(t-2002)\right), \\ F(X_{jt};\delta) =& \exp\Bigg(\delta_0 + \sum_{h=1}^{3} 1(\mathit{Group}_{jt} = h)\left(\delta_1^h \ln(PopServed_{jt}) + \delta_2^h \ln(PopServed_{jt})^2\right), \\ &+ \delta_3 \mathit{CompIndex}_{jt} + \delta_4 \mathit{WealthIndex}_{jt}\Bigg),\end{aligned}$$

where $1(\cdot)$ is the indicator function and we use the shorthand

$$\begin{aligned}PopServed_{jt} =& 1(PowerOutput_{jt} = FullPower) \cdot DMAPop_{jt} \\ &+ 1(PowerOutput_{jt} = LowPowerClassA) \cdot InterferenceFreePop_{jt}.\end{aligned}$$

$Affiliation_{jt}$ refers to nine of the eleven affiliations in Table A3. We normalize the parameter on the indicator for Spanish-language networks to zero.[83] $Group_{jt}$ refers to groupings of affiliations (detailed below). $CompIndex_{jt}$ and $WealthIndex_{jt}$ are the competitiveness and wealth indices for the DMA.[84]

We allow the share $\alpha(X_{jt};\beta)$ of advertising revenue retained as cash flow to vary flexibly by network affiliation and year. We allow for a separate time trend for Fox affiliates as their profitability grew substantially over time. The competitiveness and wealth indices $CompIndex_{jt}$ and $WealthIndex_{jt}$ account for differences in the competitive environment and demographics across DMAs. We specify non-broadcast revenue $RT(X_{jt};\gamma)$ as an exponential function of network affiliation, DMA population and interference free population for full-power stations and low-power class-A stations, respectively, and a time trend to capture the rapid growth of retransmission fees. To streamline the specification, we subsume the affiliations in Table A3 into three groups: (1) ABC, CBS, and NBC; (2) Fox, CW, and Warner Bros; (3) My Network TV, United Paramount, Spanish-language networks, and Independents. We finally specify fixed cost $F(X_{jt};\delta)$ as an exponential function that varies flexibly with DMA population and interference free population for full-power stations and low-power class-A stations, respectively, interacted with network affiliation, where we again group affiliations. The competitiveness and wealth indices $CompIndex_{jt}$ and $WealthIndex_{jt}$ account for the differential cost of operating in different DMAs.

C.1.2 Data and estimation

We combine the station-level data on advertising revenue, station characteristics, and market characteristics from BIA with the aggregated data from NAB. The NAB data yields 3,976 moments across aggregation categories and the ten years from 2003 to 2012. We drop the years 2013 and 2015 from the BIA data as 2012 is the latest year of availability for the NAB data. There are a total of 11,731 station-year observations from the BIA data that meet NAB's data collection and reporting procedure and therefore map into a table of a NAB report.

We use a simulated minimum distance estimator for the parameters $\theta = (\beta, \gamma, \delta, \sigma)$ of the cash flow model in equation (10). We draw $N^s = 100$ 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.[85] Denote by $\overline{CF}_{gt}$, CF^1_{gt}, CF^2_{gt},

[83] We exclude any TV station affiliated with other minor networks from the estimation in line with footnote 81. To predict the cash flow for such a TV station, we use its station and owner characteristics X_{jt} and the estimated parameter on the indicator for Independent.

[84] To parsimoniously capture market characteristics, we conduct a principal component analysis of the log of the market-level variables prime-age (18-54) population, average per capita disposable personal income, retail expenditures, total market advertising revenues, number of primary TV stations, and number of major network affiliates. We define the time-varying number of primary TV stations and major network affiliates based on auction-eligible TV stations contained in the BIA data from 2003 to 2013 and for 2015 but rely on the BIA data for 2015 for the remaining market-level characteristics. 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.

[85] We make no attempt to separately estimate an error term for non-broadcast revenue or fixed cost and assume it is one part of ϵ_{jt} in equation (10) due to additivity. We obtain very similar estimates when we separately estimate

and CF_{gt}^3 the mean, first, second, and third 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 $\widehat{\overline{CF}}_{gt}(\theta; \epsilon^s)$, $\widehat{CF}_{gt}^1(\theta; \epsilon^s)$, $\widehat{CF}_{gt}^2(\theta; \epsilon^s)$, and $\widehat{CF}_{gt}^3(\theta; \epsilon^s)$ 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 θ and the vector of cash flow error terms ϵ^s in draw s; we suppress their dependence on advertising revenue and characteristic data from BIA. We use similar notation, replacing $\overline{CF}$ with $\overline{RT}$ and $\overline{F}$, respectively, for the mean of the non-broadcast revenue and fixed cost distributions. To estimate θ, we match the moments of the predicted and actual distributions across aggregation categories and years. Formally, we solve

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

Our interior-point minimization algorithm terminates with a search step less than the specified tolerance of 10^{-12}. We use multiple starting values to guard against local minima.

C.1.3 Results

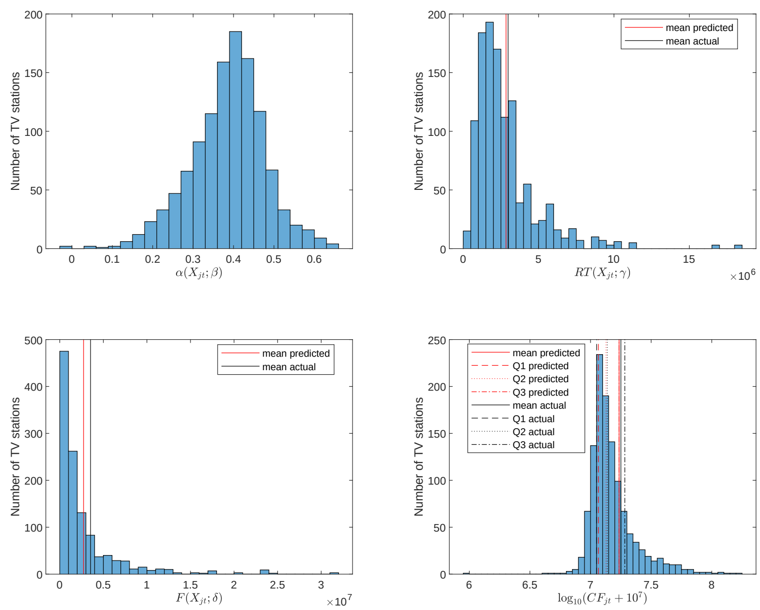
Table A6 reports the parameter estimates for the retained share $\alpha(X_{jt}; \beta)$, non-broadcast revenue $RT(X_{jt}; \gamma)$, and fixed cost $F(X_{jt}; \delta)$. Warner Bros and Spanish language networks affiliates retain the highest share of advertising revenues. Except for Fox affiliates, major network affiliates retain a higher share of advertising revenue than minor networks; however, the retained share of Fox affiliates rises over time. The retained share falls over time, bottoming out in 2009 before bouncing back in recent years. It is lower in more competitive markets and higher in more affluent markets.

Figure A3 plots the distributions of the predicted retained share $\alpha(X_{jt}; \beta)$ (upper left panel), non-broadcast revenue $RT(X_{jt}; \gamma)$ (upper right panel), and fixed cost $F(X_{jt}; \delta)$ (lower left panel) for the 1,172 commercial full-power stations surveyed by NAB in 2012. It also plots the distribution of predicted cash flow for a sample draw of the vector of cash flow error terms ϵ^s (lower right panel). We predict the retained share to be between -0.02 and 0.64 across TV stations, with an average of 0.39. Reassuringly, we predict the retained share to be negative for only two TV stations. We predict non-broadcast revenue to be between \$0.16 million and \$18.45 million, averaging \$2.84 million, and we predict fixed cost to be between \$0.00 million and \$31.25 million, averaging \$2.73 million. Finally, we predict cash flow to be between \$-9.11 million and \$151.85 million across TV stations, with an average of \$7.21 million.

The cash flow model fits the data well. In Figure A3, we overlay predicted moments as red lines and actual moments as reported in the NAB data (table "All Stations, All Markets") as black

such an error term.

Figure A3: Predicted retained share $\alpha(X_{jt};\beta)$, non-broadcast revenue $RT(X_{jt};\delta)$, fixed cost $F(X_{jt};\delta)$, and cash flow CF_{jt} with moments in 2012



Notes: In the lower right panel, cash flow is reported as $\log_{10}\left(CF_{jt}+10^7\right)$ for visual clarity.

lines. NAB reports an average non-broadcast revenue of $2.98 million compared to our prediction of $2.84 million (upper right panel). We somewhat underestimate fixed cost, where NAB reports an average of $3.53 million compared to our prediction of $2.73 million (lower left panel). Turning to cash flow (lower right panel), NAB reports an average of $7.80 million and first, second, and third quartiles of $1.24 million, $3.75 million, and $9.18 million. This compares to our predictions of $7.21 million, $1.61 million, $3.44 million, and $7.21 million, respectively.

To further assess the fit of the cash flow model, Table A7 compares the cash flow, non-broadcast revenue, and fixed cost moments reported in the NAB data to the corresponding predicted moments, broken down by type of moment, affiliation, year, and market rank. It provides three different measures of fit: the correlation between predicted and data moments, the mean absolute deviation in levels in $ million and as a percent of the data moments, and the mean deviation in levels and as a percent. Overall, our cash flow model predicts the 3,976 moments with a 0.99 correlation. The correlation between data and predicted moment ranges from 0.95 to 0.99 for the different types of moments. It is higher for the 2,394 moments pertaining to major network affiliates than for the 532 moments pertaining to minor network affiliates and independent stations. There are no systematic differences in the correlation between data and predicted moments across years. The correlation is higher for moments pertaining to larger markets. The remaining two measures of fit largely agree with the correlation.

C.2 Multiples

Our data consists of 230 transactions between 2003 and 2012 based on cash flow and 168 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 cash flow $\widehat{CF}_{jt}$ predicted using equation (7), setting $\epsilon_{jt} = 0$. For stick value transactions, we infer the stick multiple from the transaction price, the population served, and the power output of the TV station using equations (8) and (9).

For cash flow transactions, we project the log of the multiple on station, owner, and market characteristics using the model:

$$\ln Multiple^{CF}_{jt} = \beta^{CF} X_{jt} + \epsilon^{CF}_{jt}. \tag{A1}$$

In X_{jt} we flexibly include the DMA population and interference free population for full-power stations and low-power class-A stations, respectively, interacted with network affiliation, where we group affiliations into major and minor networks according to Table A3. We further include the wealth and competitiveness indices, the number of TV stations in the DMA, ownership category fixed effects (whether the owner owns between two and ten, or more than ten TV stations across DMAs), a low-power class-A fixed effect, a minor network fixed effect, a fixed effect for independent stations, and a full set of year fixed effects.

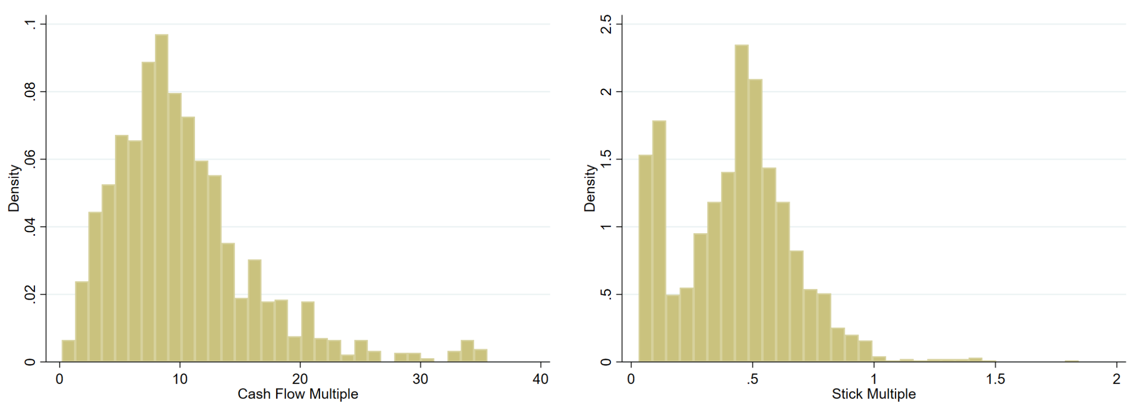
For stick value transactions, we use the model:

$$\ln Multiple^{Stick}_{jt} = \beta^{Stick} X_{jt} + \epsilon^{Stick}_{jt}. \tag{A2}$$

In X_{jt} we flexibly include the DMA population and interference free population for full-power stations and low-power class-A stations, respectively. We further include the wealth and competitiveness indices, the number of TV stations in the DMA, ownership category fixed effects, the output power of the TV station and its interaction with an indicator for the period prior to the TV station's transition to digital transmission, a low-power LPTV fixed effect, a full-power fixed effect, a fixed effect for satellite stations, and a full set of year fixed effects.

Table A8 reports parameter estimates for the cash flow and stick value multiples. The adjusted R^2 is 0.82 for both models, suggesting that they fit the data well. With the estimates in hand, we predict the cash flow and stick multiples for the 1,670 UHF stations located in the U.S. excluding Puerto Rico and the Virgin Islands that the FCC has declared as eligible for the reverse auction. We set $\epsilon^{CF}_{jt} = \epsilon^{Stick}_{jt} = 0$ to predict. Figure A4 illustrates the distributions of the predicted cash flow multiple (left panel) and stick multiple (right panel).

Figure A4: Distributions of predicted cash flow and stick multiples



D Robustness to full repacking

We perform two exercises to assess the effect of the limited repacking described in Section 6.2. First, we compare limited to full repacking for all 202 DMAs under naive bidding and both the 84 MHz and the 126 MHz clearing target. Table A9 shows that moving to full repacking reduces total payouts by 0.2% under the 126 MHz clearing target and by 1.5% under the 84 MHz clearing target. This payout reduction is driven by the smaller number of TV stations that are acquired in the reverse auction under the more flexible full repacking, as Table A9 shows. A lowering of the clearing target, and the smaller number of TV stations that need to be acquired to meet it, amplifies this effect. Closer inspection shows that the differences in payouts under full and limited repacking are minor: the largest discrepancy across simulation draws is in the San Diego, CA, DMA

(\$341 thousand) at the 126 MHz clearing target and in the New York, NY, DMA (\$41 thousand) at the 84 MHz clearing target. At the same time, the correlation between payouts under full and limited repacking is 1.0000 for the 126 MHz clearing target across DMAs and simulation draws and 0.9998 for the 84 MHz clearing target, suggesting that limited repacking captures the distribution of payouts well.

Second, we compare limited to full repacking under strategic bidding for the New York, NY, DMA, as doing so for all 202 DMAs is not computationally feasible. As Table A10 shows, limited repacking has a modest impact on payouts in the New York, NY, DMA and on the gains from strategic bidding for both the 126 MHz and the 84 MHz clearing target.

E Binary programming problem

There are N TV stations in the focal DMA and its neighbors with reservation values $(v_1, \dots, v_N)$ in a given simulation draw. The clearing target defines the set of channels R that are available for repacking TV stations that remain on the air. Define the indicator $x_{j,c}$ to equal one if TV station j is assigned to channel c and zero otherwise. Consequently, TV station j remains on the air if $\sum_c x_{j,c} > 0$. Define $I(x) = \{j | \sum_c x_{j,c} > 0\}$ to be the set of all TV stations that remain on the air, where x is the vector of assignments of TV stations to channels. We solve the binary programming problem

$$\max_x \sum_j \sum_c x_{j,c} v_j \tag{A3}$$

subject to $S(I(x), R) = 1$ and $\sum_c x_{j,c} \leq 1$ for all j. The first constraint ensures that the assignment of TV stations to channels is feasible and the second constraint that a TV station is either assigned a single channel or goes off the air.

In practice, instead of calling the feasibility checker $SATFC$, we follow Newman et al. (2017) and add the underlying constraints from the domain and pairwise interference files described in Section 4.2 to the binary programming problem. For a given clearing target, define R_j to be the set of channels that are available for repacking TV station j per the domain file and Q to be the set of all pairs of TV stations and channel assignments that are not feasible per the pairwise interference file. We solve the binary programming problem in equation (4.2) subject to

$$x_{j,c} + x_{j',c'} \leq 1 \text{ for all } (j, c, j', c') \in Q,$$
$$\sum_c x_{j,c} \leq 1 \text{ for all } j,$$
$$x_{j,c} = 0 \text{ for all } c \notin R_j \text{ and all } j.$$

The first constraint enforces that TV stations j and j' cannot be assigned channels c and c', respectively, if this is not feasible per the pairwise interference file. In case of a same-channel constraint between TV stations j and j', we have $c = c'$, and in case of an adjacent-channel constraint, we have $c = c' \pm 1$. As both the objective function and the constraints are linear, we use CPLEX to solve the binary programming problem.

Table A4: NAB tables in 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

Table A5: Sample NAB data for select aggregation categories in 2012

	Advertising revenue ($ million)	Cash flow ($ million)				Non-broad-cast revenue ($ million)	Fixed cost ($ million)
			Quartile				
	Mean	Mean	First	Second	Third	Mean	Mean
All Stations, All Markets	16.96	7.80	1.24	3.75	9.18	2.98	3.53
All Stations, Markets 101-110	8.27	4.12	1.70	3.62	6.44	2.10	2.46
ABC, CBS, FOX, NBC, All Markets	19.05	9.24	1.94	4.93	10.90	3.33	3.99
ABC, Markets 1-25	67.78	32.40	15.09	27.15	42.46	7.60	9.76
NBC, Markets 101+	7.57	3.65	1.29	3.28	5.90	1.88	2.19
CW, All Markets	13.35	3.93	0.35	1.80	3.22	2.88	2.60
MNTV, Markets 1-50	9.49	3.12	1.27	1.80	3.21	2.51	2.02
Independent, All Markets	13.43	2.79	-0.02	1.29	4.33	2.20	3.27

Table A6: Cash flow parameters estimates

	Estimate
Retained share $\alpha(X_{jt};\beta)$	
ABC	-0.1136
CBS	-0.0949
NBC	-0.0743
Fox	-0.3942
CW	-0.1405
Warner Bros	0.0029
MyNetwork TV	-0.3067
United Paramount	-0.3735
Spanish-language networks (normalized)	0
Independent	-0.1489
Fox × Trend	0.0201
2003	0.5887
2004	0.5663
2005	0.5473
2006	0.5321
2007	0.4981
2008	0.4640
2009	0.3960
2010	0.4839
2011	0.4886
2012	0.5126
$CompIndex_{jt}$	-0.0365
$WealthIndex_{jt}$	0.0314
Non-broadcast revenue $RT(X_{jt};\gamma)$	
Group 1	9.0679
Group 2	8.5738
Group 3	7.9961
$\ln(PopServed_{jt})$	0.6179
Trend	0.1511
Fixed cost $F(X_{jt};\delta)$	
Intercept	-5.4063
Group1 × $\ln(PopServed_{jt})$	5.4144
Group2 × $\ln(PopServed_{jt})$	4.5645
Group3 × $\ln(PopServed_{jt})$	5.0257
Group1 × $\ln(PopServed_{jt})^2$	-0.3604
Group2 × $\ln(PopServed_{jt})^2$	-0.2685
Group3 × $\ln(PopServed_{jt})^2$	-0.3312
$CompIndex_{jt}$	-0.2054
$WealthIndex_{jt}$	0.6919
Standard deviation σ	1.1476

Table A7: Cash flow, non-broadcast revenue, and fixed cost moments and fit measures

	Number of		Mean abs. deviation		Mean deviation	
	moments	Correlation	$ million	%	$ million	%
All moments	3976	0.984	0.746	0.157	-0.011	-0.002
Moments by type						
Cash flow, mean	663	0.989	0.815	0.121	-0.131	-0.019
Cash flow, first quartile	662	0.969	0.744	0.290	0.054	0.021
Cash flow, second quartile	663	0.980	0.881	0.174	0.036	0.007
Cash flow, third quartile	663	0.985	1.195	0.133	0.056	0.006
Non-broadcast revenue, mean	662	0.939	0.302	0.178	0.046	0.027
Fixed cost, mean	663	0.964	0.540	0.153	-0.125	-0.036
Moments by affiliation						
Major network	2394	0.986	0.833	0.142	0.037	0.006
Minor network	420	0.942	0.763	0.302	0.034	0.013
Independent	132	0.826	0.659	0.382	0.043	0.027
Moments by year						
2003	395	0.984	0.845	0.170	0.082	0.017
2004	390	0.989	0.713	0.133	-0.041	-0.008
2005	396	0.985	0.736	0.157	0.109	0.023
2006	372	0.990	0.681	0.124	-0.137	-0.025
2007	413	0.987	0.721	0.163	0.059	0.013
2008	420	0.980	0.735	0.178	-0.085	-0.021
2009	396	0.975	0.588	0.200	0.009	0.003
2010	396	0.982	0.746	0.153	-0.079	-0.016
2011	402	0.973	0.827	0.179	0.127	0.028
2012	396	0.985	0.867	0.139	-0.161	-0.026
Moments by market rank						
1-25	552	0.982	1.935	0.132	0.142	0.010
26-50	462	0.956	0.829	0.147	-0.115	-0.021
50-100	1116	0.937	0.518	0.167	-0.134	-0.043
101+	959	0.872	0.422	0.280	0.083	0.055

Table A8: Cash flow and stick value multiples parameter estimates

	Cash flow multiple		Stick multiple	
	Estimate	Std. Err.	Estimate	Std. Err.
$\ln(PopServed_{jt})$	0.3176**	(0.1350)	-0.6585***	(0.1982)
× Minor network	1.8581***	(0.5747)		
× Major network	0.3292	(0.3955)		
$\ln(PopServed_{jt})^2$	0.0106	(0.0152)	0.0241	(0.0198)
× Minor network	-0.1674***	(0.0438)		
× Major network	-0.0167	(0.0353)		
$WealthIndex_{jt}$	-0.0611	(0.0470)	0.0717	(0.0721)
$CompIndex_{jt}$	0.0518	(0.0896)	0.1588	(0.1928)
# Stations in DMA	0.0006	(0.0073)	-0.0076	(0.0162)
Owns 2-10 stations across DMAs	0.0021	(0.1527)	0.0617	(0.2736)
Owns >10 stations across DMAs	-0.2263	(0.1587)	0.0317	(0.3034)
$\ln(OutputPower_{jt})$			0.2452***	(0.0769)
$\ln(OutputPower_{jt})$ × Predigital			-0.1060	(0.0688)
Low-power class-A	-0.3335**	(0.1561)		
Low-power LPTV			-1.3881***	(0.2725)
Full-power			0.9531**	(0.3923)
Satellite			1.4541	(0.8805)
Independent	-4.3615**	(1.8785)		
Minor network	-1.4903	(1.1023)		
2004	-0.3205	(0.2877)	0.7308	(0.6316)
2005	0.2548	(0.2569)	1.1848**	(0.5373)
2006	-0.0359	(0.2815)	0.9274*	(0.5225)
2007	-0.1179	(0.2569)	1.3040**	(0.6037)
2008	-0.4977*	(0.2960)	0.0368	(0.5861)
2009	-0.435	(0.4586)	0.2331	(0.4798)
2010	-0.3297	(0.3282)	-1.1143**	(0.5508)
2011	-0.8047***	(0.2720)	-0.2103	(0.5562)
2012	-1.1719***	(0.2445)	0.1228	(0.5372)
2013	-0.8447***	(0.2306)	-0.7057	(0.4918)
Adjusted R^2	0.8192		0.8182	
N	402		253	

Table A9: Nationwide payouts to TV stations and number of TV stations acquired under naive bidding and full repacking

	Naive bidding	
	Payouts ($ billion)	Number of TV stations acquired
Panel A: 126 MHz clearing target		
Limited repacking	15.767	452.022
	(2.639)	(11.052)
Full repacking	15.734	441.600
	(2.637)	(9.153)
Panel B: 84 MHz clearing target		
Limited repacking	2.477	182.609
	(0.361)	(8.942)
Full repacking	2.441	160.580
	(0.356)	(4.985)

Table A10: Payouts to TV stations in New York, NY, DMA under strategic bidding and full repacking

Payouts ($ billion)	Naive bidding	Strategic bidding				Payout increase at mean (%)
		Mean	Min	Median	Max	
Panel A: 126 MHz clearing target						
Limited repacking	3.072	5.100	4.369	5.053	5.889	66.0
	(1.169)	(2.119)	(2.125)	(2.204)	(2.628)	
Full repacking	3.072	5.039	4.323	5.023	5.788	64.0
	(1.169)	(2.082)	(2.076)	(2.141)	(2.592)	
Panel B: 84 MHz clearing target						
Limited repacking	0.373	0.415	0.403	0.415	0.428	11.3
	(0.117)	(0.127)	(0.124)	(0.128)	(0.135)	
Full repacking	0.371	0.409	0.394	0.408	0.422	10.0
	(0.116)	(0.127)	(0.121)	(0.131)	(0.132)	

Notes: Payout increase at mean calculated as percent difference between mean payouts under strategic and naive bidding.