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 and simulation exercise, we find that this strategic supply reduction 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. Between the reverse and the forward auctions, the FCC "repacks" all TV stations that opt to remain on the air to clear a contiguous, nationwide block of spectrum for mobile broadband usage. 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 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. 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. Using a large-scale valuation and simulation exercise, we show that this strategy of reducing supply affects a large transfer of wealth from the government—and ultimately taxpayers—to TV stations.

Re-purposing spectrum from broadcast TV to mobile broadband usage is an extremely valuable and—due to the repacking process that sits between the reverse and the forward auctions—complex undertaking, and the incentive auction was 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,

[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.

then it would be a dominant strategy for each TV station to truthfully 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 to illustrate how strategic supply reduction works in the context of the reverse auction and highlight the circumstances under which 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 conduct a simulation exercise to compare the outcome of the reverse auction 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.

A striking result of our simulation exercise is that the outcome of the reverse auction is sensitive to small changes in bidding behavior: withholding relatively few TV stations suffices to give rise

[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.

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), by estimating reservation values from secondary, commercially available data and taking 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.

To illustrate the usefulness of the framework we provide, we show that the transfer from the government to TV stations due to strategic supply reduction can be greatly reduced by relatively simple changes in the design of the reverse auction. First, we propose a 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 their observed 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 the 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 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

[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.

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).

Our simulation exercise substantially underpredicts payouts in the actual reverse auction. We trace 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. Section 6 describes our large-scale valuation and simulation exercise. Section 7 quantifies the impact of ownership concentration and strategic supply reduction on the reverse auction. Section 8 uses our framework to assess the design of the reverse auction and modifications to it in order to mitigate the impact of ownership concentration. Section 9 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. At the same time, some previously allocated spectrum is no longer used intensively. Over 8,400 operating TV stations in the U.S. as of 2012 each hold a license to a six MHz block of spectrum in a particular geographical area dedicated to over-the-air transmission of programming.[6] Yet, only about 10% of TV households use broadcast TV as of 2010, with a rapidly declining trend.[7]

To reallocate spectrum from TV stations to wireless carriers, the FCC proposed to conduct an incentive auction in its 2010 National Broadband Plan. 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.

While the incentive auction is the first time the FCC combined an auction to sell spectrum with an auction to buy spectrum from existing licensees, it has used auctions since 1993 to award licenses for the commercial use of spectrum. Auctions as a market-based mechanism rely on voluntary participation and are relatively robust to legal challenges. 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.

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.[8]

Reverse auction. The reverse auction uses a descending-clock format that we describe in detail in Section 3. The FCC initially declared 2,197 TV stations as eligible for the reverse auction but then revoked the licenses of three TV stations, resulting in 2,194 auction-eligible TV stations.[9] 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, 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.[10]

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), or

[6] See https://www.tvtechnology.com/news/total-number-of-us-tv-stations-continues-decline, accessed on June 22, 2023.

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

[8] 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.

[9] See http://wireless.fcc.gov/auctions/incentive-auctions/Reverse_Auction_Opening_Prices_111215.xlsx, accessed on March 7, 2018. The FCC revoked the licenses of KLHU-CD, DWKOG-LP, and WDHS.

[10] A satellite station is a relay that repeats the broadcast TV signal of its parent primary station. The FCC excludes low-power non-class-A and translator stations from the reverse auction.

sharing a channel with another TV station.[11] 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. A TV station cannot on its own choose to re-purpose 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 as of 2015.

The 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 six states (CT, NJ, NY, MA, PA, and RI) whereas the New York, NY, PEA consists of 42 counties in four 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 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 the VHF band. This process is visually similar to defragmenting a hard drive on a personal computer and creates a contiguous block of spectrum for mobile broadband usage in the higher end of the UHF band.

However, the repacking process is far more complex than defragmenting a hard drive 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. The resulting interference constraints have two consequences. First, the repacking process ties together all DMAs and effectively takes place at the national level. Second, because it must accommodate interference constraints, the reverse auction becomes computationally demanding. Checking the feasibility of repacking a set of TV stations into a set of available channels is an NP-hard problem. Indeed, the FCC had to pause the reverse auction on occasion because it failed to solve this problem on time.[12]

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

[11] Lower frequencies are less desirable for wireless carriers. While the FCC piloted a channel-sharing arrangement in Los Angeles, CA in 2014, it is unclear how attractive this relinquishment option is because channel sharing may no longer be technologically feasible once TV stations transition from high-definition to ultra-high-definition (4K) video streams. See https://www.fiercewireless.com/wireless/fcc-approves-broadcast-spectrum-sharing-pilot-for-l-a-tv-stations, accessed on June 22, 2023.

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

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.

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.[13]

Timeline and outcome. Congress authorized the incentive auction in 2012 and the FCC publicly announced its format in 2014.[14] Technological and legal challenges delayed the starting date of the incentive auction from 2014 to March 29, 2016.[15]

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.[16] The FCC concluded the process of reassigning channels to the TV stations that opted to remain on the air in 2020.[17]

[13]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.

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

[15]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.

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

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

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 auction-eligible 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.[18] The 175 TV stations that relinquished their licenses are located in 62 DMAs and payouts in the reverse auction are concentrated in a small number of DMAs, with the New York, NY, DMA accounting for 14.1% of the $10.1 billion payout, followed by the Los Angeles, CA, DMA with 13.2% and the Philadelphia, PA, DMA with 10.4%. Overall, ten DMAs account for 75.5% of the $10.1 billion payout.

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 subsequently reversed this decision. The FCC had 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, and several chains of commercial TV stations had early on shown little interest in the reverse auction, with the CEO of Sinclair Broadcasting Group declaring that he "hasn't heard of any broadcaster who has said they have anything for sale."[19] Klemperer (2016) and Milgrom and Segal (2020) similarly point to participation as a primary concern for auction design. The additional data that the FCC recently released shows that 1,029 out of 2,194 auction-eligible TV stations participated in the reverse auction. Our ownership data for the continental U.S. show that, contrary to the FCC's expectations of low participation by sentimental owners, participation was higher among independently-owned TV stations (54.09%) than among TV stations that are part of a chain (39.65%).

As the first public version of this research paper appeared while the auction was still ongoing, we do not use the recently released data with two exceptions. First, we use the data to validate our estimated reservation values in Section 6.1. Second, while our ex-ante analysis of the reverse auction conservatively assumes that all eligible TV stations participate in the reverse auction, we use the data to assess the sensitivity of the reverse auction to reduced participation in Section 7.2.

3 A model of the reverse auction

We illustrate the impact of ownership concentration and the potential for strategic supply reduction in a model of the reverse auction. We leverage that the auction design limits interactions between the reverse and forward auctions and take the clearing target as given in our analysis.

The reverse auction is a deferred-acceptance clock auction.[20] 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

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

[19] See `http://www.tvnewscheck.com/article/73196/wheeler-auction-onceinalifetime-chance`, accessed on March 18, 2018 and "FCC can auction spectrum, but will broadcasters sell?", Joe Flint, The Los Angeles Times, February 17, 2012.

[20] Our model draws on Appendix D of FCC Public Notice 14-191 and Milgrom and Segal (2020). See Bikhchandani et al. (2011) and the references therein for earlier work on deferred-acceptance auctions.

clock price in round $\tau \geq 1$. The base clock price maps into a "personalized" price $\varphi_j P_\tau$ for TV station j through its broadcast volume, defined as[21]

$$\varphi_j = 17.253\sqrt{InterferenceFreePop_j \cdot InterferenceCount_j}. \tag{1}$$

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 to 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.[22]

The base clock price P_τ decreases over the course of the auction reverse. 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.[23] 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 $X \subseteq \{1, \ldots, N\}$ can be repacked into a set of available channels R and zero otherwise.[24] 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.

In round τ of the reverse auction, the set of TV stations $\{1, \ldots, N\}$ 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 becomes inactive and may freeze one or more other active TV stations if the FCC can no longer guarantee a channel assignment for these stations. 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 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 $F_1 = \emptyset$. The reverse auction concludes after round τ if the base clock price reaches zero or no active TV stations remain, i.e., if $P_{\tau+1} = 0$ or $A_{\tau+1} = \emptyset$.[25]

The auction design ensures that the FCC is able to assign a channel to any TV station that

[21] The scale factor $M = 17.253$ ensures $\max_{j\in\{1,\ldots,N\}} \varphi_j = 1,000,000$.

[22] 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.

[23] 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.

[24] 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 $UNSAT$.

[25] 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 $P_{\tau+1} = 0$.

withdraws from reverse auction at any point. Suppose that given its personalized price $\varphi_j P_\tau$, active TV station $j \in A_\tau$ withdraws from the reverse auction in round τ and collects the payout $PO_j = 0$.[26] The FCC then checks if it can guarantee a channel for each remaining active TV station $j' \in A_\tau \setminus \{j\}$ in round $\tau + 1$. If, as a consequence of TV station j withdrawing, the FCC cannot guarantee a channel for TV station j', i.e., if $S(I_\tau \cup \{j\} \cup \{j'\}, R) = 0$, then TV station j' is frozen and collects the payout $PO_{j'} = \varphi_{j'} P_\tau$ in return for relinquishing its license. At the conclusion of this process of feasibility checking, the FCC can guarantee a channel for each remaining active TV station going into round $\tau + 1$.

The reverse auction defines an extensive-form game. To complete its description, we specify the information sets of the TV stations. The FCC 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.[27] 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.[28] We henceforth 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. While our analysis proceeds with a game of complete information, in Online Appendix A.3, we show that our notion of strategic supply reduction in settings with jointly owned TV stations extends to incomplete information. We do not assume that the FCC knows the reservation values of the TV stations.

3.1 Strategic supply reduction

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). 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 an example to illustrate that a firm owning multiple TV stations may have an incentive

[26] 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. 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. 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).

[27] 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.

[28] 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).

to deviate from naive bidding. Hence, naive bidding may no longer be an equilibrium if TV stations are jointly owned. Instead, the equilibrium entails strategic supply reduction.

There are $N = 3$ TV stations with the reservation values and broadcast volumes as follows:

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

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 $1,800$.

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.

Generalizing of the example sheds light on 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 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.

3.2 Multiple equilibria

While strategic supply reduction is part and parcel of the reverse auction, our example admits multiple equilibria. In Online Appendix A.1, we show that the set of equilibria is

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

We also show that multiple equilibria arise even if we impose the single-mindedness assumption of Milgrom and Segal (2020) on the example as though all TV stations were independently owned. Focusing on truthful bidding as a dominant strategy amounts to singling out a particular equilibrium.

As can be seen from expression (3), the auction rules 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.[29] Strategic supply reduction is an extreme form of overbidding $b_j > s_j$ in that a firm

[29] The equilibria the second line of equation (3) 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,

withholds one or more of the TV stations it owns from the reverse auction. The equilibria may also entail milder forms of overbidding and underbidding $b_j < s_j$.

Given the large number of participating TV stations and the complex ownership patterns and interference constraints in the actual reverse auction, we restrict the strategy space in our subsequent analysis. In particular, we assume that the strategy space of TV station j is $b_j = s_j$ if it is independently owned and $b_j \in \{s_j, 900\}$ if it is jointly owned. For an independently owned TV station, we therefore follow Milgrom and Segal (2020) by focusing on truthful bidding as a dominant strategy. For jointly owned TV stations, we rule out milder forms of overbidding and underbidding.

These restrictions on jointly owned TV stations are not overly arduous. In Online Appendix A.2, we show 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 $b_j = 900$ ensures a strictly higher profit. Turning from overbidding to underbidding, we also show that if a firm owning multiple TV stations finds it more profitable to underbid $b_j < s_j$ than to truthfully bid $b_j = s_j$, then the firm may as well bid $b_j = 0$. Finally, in Online Appendix G.2, we show that restricting the strategy set from $b_j \in \{0, s_j, 900\}$ to $b_j \in \{s_j, 900\}$ for jointly owned TV station j has a small impact on payouts in the computationally manageable New York, NY, DMA under the 84 MHz clearing target.

4 Data sources

In the remainder of the paper, we turn to assessing the impact of ownership concentration on the actual reverse auction. To quantify how the outcome differs between strategic bidding under the actual ownership pattern and truthful bidding under the counterfactual of independent ownership, we combine estimated reservation values with simulation techniques.

We first describe the various data sources we combine to infer the reservation values of the TV stations participating in the reverse auction and to determine their ownership structure, with further details provided in Online Appendix B. Then we turn to the interference constraints on the repacking process.

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.

4.1 Reservation values and ownership structure

We infer the reservation value of a TV station by modeling the components of its cash flow, focusing on advertising revenue, non-broadcast revenue, and fixed cost, as detailed in Section 6.1.[30] We estimate this model using the MEDIA Access Pro Database from 2003 to 2013 and for 2015 from BIA Kelsey (henceforth BIA) and the Television Financial Report from 2003 to 2012 from the National Association of Broadcasters (NAB).

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 Online Appendix B.1. 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.[31] To get at non-broadcast revenue and fixed cost, we use the NAB data. As detailed in Online Appendix B.2, 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, such as "ABC, CBS and NBC affiliates in markets ranked 51-60 in 2012" or "CBS affiliates in markets ranked 1-50 in 2012". 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.[32] 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 repacking yields the set of available channels R described in Section 3.

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

[31] Retransmission fees are a small but growing source of revenue. See "SNL Kagan raises retrans fee forecast to $9.8B by 2020; Mediacom's CEO complains to FCC", FierceCable, July 7, 2015.

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

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 in the repacking process; these are the interference constraints that we suppress in our notation for the indicator function $S(X, R)$. 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,[33] the FCC applied an existing standard of 0.5%, meaning that a TV station's population served cannot decrease by more than 0.5% in the repacking process. For an interference level of 0.5%, the pairwise interference file imposes 1,626,176 restrictions on the repacking process under a 126 MHz clearing target with UHF channels 14-29 available for repacking; the number of restrictions grows to 2,334,334 under an 84 MHz clearing target with UHF channels 14-36 available for repacking.

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.[34]

5 Descriptive evidence

We provide descriptive evidence in support of ownership concentration and strategic supply reduction. From hereon, we restrict attention to the 1,670 auction-eligible UHF stations that are located outside Puerto Rico and the Virgin Islands.[35] These TV stations are assigned to 202 DMAs.

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. Our analysis of the reverse auction focuses on multi-license ownership within DMA; we come back to multi-license ownership across DMAs in Section 7.2.

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

[34] 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.

[35] Out of the 145 TV stations that went off the air, seven are located in Puerto Rico. These seven TV stations together claimed less than 0.5% of payouts in the reverse auction. The 480 auction-eligible VHF stations together claimed a mere 3.7% of payouts in the reverse auction.

Table 1: 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

In June 2014, the FCC conducted its own simulations to assess the likely number of TV stations in each DMA that have to relinquish their licenses for a clearing target of 120 MHz (84 MHz) to be met.[36] Juxtaposing all 202 DMAs with the 119 (79) DMAs for which the FCC assessed positive demand, Table 1 provides further details on ownership concentration. 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 1 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, relative to 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 in effect during the incentive auction 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 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. They do not apply to non-commercial, low-power, and satellite stations, and waivers can be—and have been—granted for failing or financially

[36] As described in "Appendix: Analysis of Potential Aggregate Interference" of FCC Public Notice DA 14-677, 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 27 (25) simulations for the 120 MHz (84 MHz) clearing target. 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.

distressed TV stations.[37] As our data and analysis show, these rules may not preclude firms from accumulating market power in the reverse auction through multi-license ownership.

5.2 Private equity firms

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.

We manually collected data on the private equity firms and their acquisitions, as detailed in Online Appendix C. 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, many of them are failing or in financial distress, and most 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 the goal of flipping TV stations mentioned above, the private equity firms appear to have targeted DMAs with robust "demand".

At the same time, however, the private equity firms accumulated market 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 ten TV stations acquired by LocusPoint are located in ten different DMAs, as are the 15 TV stations acquired by NRJ and the 23 TV stations acquired by OTA. In Online Appendix C.2, we show that the 48 TV stations acquired by the three private equity firms tend to have higher broadcast volume, due to both higher interference free population and higher interference count, than other TV stations transacted from 2010 to 2013. The 48 TV stations acquired are therefore relatively more difficult to assign to a channel in the repacking process if they opt to remain on the air and the base clock price is "magnified" by their relatively high broadcast volume if they 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. Separately for LocusPoint, NRJ, and OTA, Table 2 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

[37] 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.

Table 2: 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

table also indicates the profit made or loss incurred on these latter two sets of TV stations. 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. We estimate their return on investment to range from -24% for LocusPoint to 199% for NRJ to 509% for OTA.[38]

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 Reservation values and simulation exercise

We first describe how we infer the reservation value of a TV station going into the reverse auction, with further details provided in Appendix A. With reservation values in hand, we turn to the large-scale simulation exercise that we use to assess the impact of strategic bidding under the ownership pattern in the data on the reverse auction.

6.1 Reservation values

In close resemblance to how market participants and industry consultants value a TV station,[39] we model the reservation value of TV station j in year t_0 as the greater of its cash flow value $v^{CF}_{jt_0}$ and

[38]These estimates are lower bounds as each private equity firm continues to own one TV station.

[39]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.

its "stick" value $v_{jt_0}^{Stick}$:

$$v_{jt_0} = \max\left\{v_{jt_0}^{CF}, v_{jt_0}^{Stick}\right\}. \tag{4}$$

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

$$v_{jt_0}^{CF} = Multiple_{jt_0}^{CF} \cdot CF_{jt_0}. \tag{5}$$

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 $Multiple_{jt_0}^{Stick}$. 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

$$v_{jt_0}^{Stick} = Multiple_{jt_0}^{Stick} \cdot 6\, MHz \cdot InterferenceFreePop_{jt_0}. \tag{6}$$

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.[40] We therefore use DMA population to measure population served. Hence, the stick value of a full-power station is

$$v_{jt_0}^{Stick} = Multiple_{jt_0}^{Stick} \cdot 6\, MHz \cdot DMAPop_{jt_0}. \tag{7}$$

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.

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

$$CF_{jt} = \alpha\left(X_{jt};\beta\right) AD_{jt} + RT\left(X_{jt};\gamma\right) - F\left(X_{jt};\delta\right) + \epsilon_{jt}, \tag{8}$$

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. Because only advertising revenue AD_{jt} and station and market characteristics X_{jt} are directly observable in the BIA data, 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.

[40] Any cable operator offering more than twelve 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.

We use a simulated minimum distance estimator. The parameters $\theta = (\beta, \gamma, \delta, \sigma)$, together with our functional form and distributional assumptions in equation (8), 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 (8) 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 the transactions for TV stations 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. 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 (5), (6), and (7), respectively. We regress 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. These regressions allow us to predict multiples for any TV station, not just those that were recently transacted. In line with outside analysts, for the 1,670 auction-eligible UHF stations located outside Puerto Rico and the Virgin Islands we predict 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.[41]

Reservation values. The aggregated data from NAB that we use to estimate the cash flow model in equation (8) does not cover all 1,670 TV stations. The omissions are 387 low-power class-A stations, 289 non-commercial stations, and 4 dark stations 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 $t_0 = 2015$.[42] 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 six MHz of its license with the TV station's estimated stick multiple.[43]

[41] 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.

[42] 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.

[43] We thus do not account for estimation error in the parameters of the cash flow model in equation (5) and the multiples models in equations (A1) and (A2) in Appendix A.2.

As specified in equations (4)–(7), 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.

We use $N^s = 100$ draws of reservation values in our simulation exercise. 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. The average TV station has a reservation value of \$51.1 million as the cash flow value is often higher than the stick value. Reservation values correlate with advertising revenues and network affiliation and 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 evidence 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,[44] and finally to those TV stations that do not share an owner with another TV station across the U.S. Because truthful 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 3 reports the estimates along with an F-test that the coefficient on the estimated reservation value is one.[45] Panel A pertains to the sample of cash-flow-valued stations, panel B 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

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

[45]We reach the same conclusions if we alternatively use a joint test that the constant is zero and the coefficient on the estimated reservation value is one.

Table 3: Regression of dropout points on constant and estimated reservation values

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

from the dropout points for individual TV stations.[46] It is perhaps not surprising that our estimated reservation values 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

Our goal is to enumerate all equilibria of the reverse auction in order to assess the scope for strategic supply reduction. This requires running the reverse auction for all strategy profiles and for $N^s = 100$ draws of reservation values to account for randomness.

The number of strategy profiles is extremely large because we assume in line with our ex-ante perspective that all eligible TV stations participate in the reverse auction and that the strategy

[46]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. We estimate the reservation values of six other TV stations to be in the billion dollar range. Similar to KCBS-TV, these TV stations are major network affiliates in the New York, NY, Los Angeles, CA, Chicago, IL, and Atlanta, GA, DMAs. Besides KCBS-TV, only WNBC participated in the reverse auction. It withdrew from the reverse auction at a price of $214 million by entering a channel sharing agreement with WNJU . We do not know the reason behind the low dropout point of KCBS-TV and drop it as outlier from the sample of cash-flow-valued stations in Table 3.

space of TV station j is $b_j \in \{s_j, 900\}$ if it is jointly owned. Of the 1,670 auction-eligible UHF stations that are located outside Puerto Rico and the Virgin Islands, 1,368 are part of a chain. A small simplification arises because the FCC determined that 247 of the 1,670 TV stations can always be assigned a UHF channel under any clearing target. The FCC declared these TV stations as "not needed" and bared them from participating.[47] We henceforth set the strategy space of TV station j to $b_j = 900$ if it is not needed, as this is equivalent to not participating in our model of the reverse auction. The number of strategy profiles nevertheless remains extremely large. Computational feasibility therefore demands further assumptions and simplifications.

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. 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. This breaks up the national problem into multiple regional problems, one for each of the 202 DMAs. 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). 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.

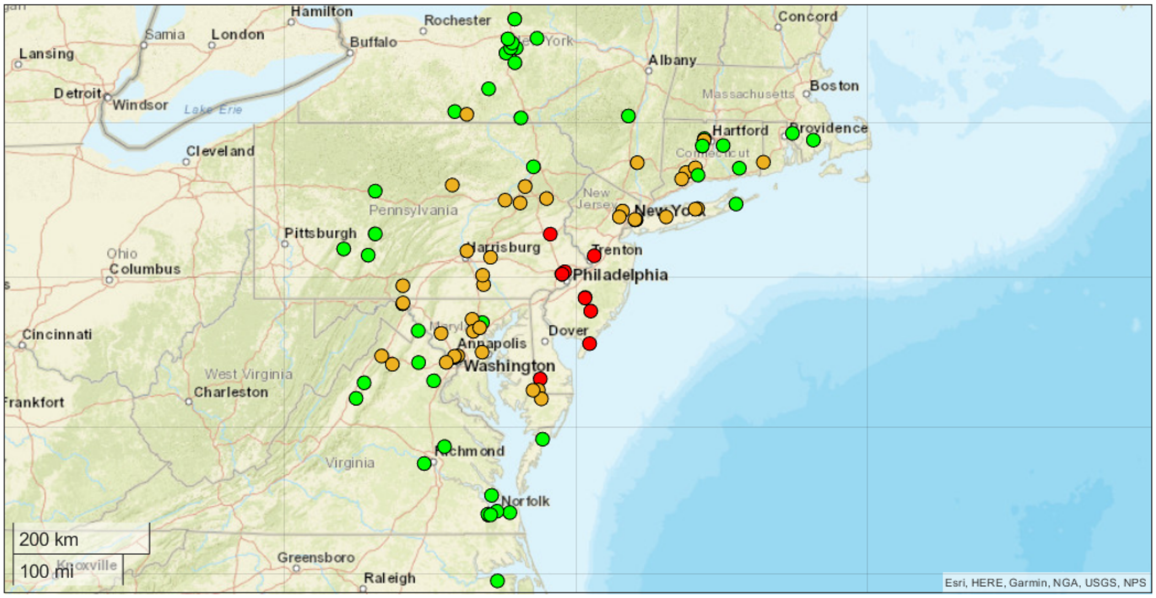
We base our definition of a region on the interference constraints for the 1,670 auction-eligible UHF stations that are located outside Puerto Rico and the Virgin Islands and UHF channels 14-29 that are available for repacking under the 126 MHz clearing target. This definition is invariant to alternative clearing targets. In Online Appendix D, we show that a region is generally much larger than a DMA. On average, a region covers about eleven DMAs. It has about 19 times as many TV stations and is about 18 times larger in area than the focal DMA.

Figure 1 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 1), while 138 are located outside the Philadelphia, PA, DMA (yellow and green dots) in one of 15 other DMAs. Moreover, 63 of the 138 TV stations do not have an interference constraint with any TV station located inside the Philadelphia, PA, DMA (green dots); they are nevertheless part of the region and may thus affect the payout for a TV station in the focal DMA.

Our baseline is the outcome of the reverse auction under naive bidding, where we ignore the

[47] 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 as not needed but revoked its license prior to the reverse auction, see footnote 9.

Figure 1: 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.

ownership patterns in the data and counterfactually treat all TV stations as independently owned. Hence, unless TV station j is not needed and bids $b_j = 900$, it bids $b_j = s_j = \frac{v_j}{\varphi_j}$, where v_j is its reservation value and φ_j its broadcast volume. We simulate the reverse auction under naive bidding for $N^s = 100$ draws of reservation values. In Online Appendix F, 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 $b_j = 900$ (unless TV station j is not needed). 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).[48] This assumption is conservative in that it limits the scope for strategic supply reduction by abstracting from multi-license ownership across DMAs; we come back to it in Section 7.2.

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

[48] 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.

station. In Online Appendix F, we provide pseudo code for the modified algorithm.

This modification significantly reduces the computational burden.[49] In Online Appendix G.1, we show that nationwide payouts under naive bidding and limited repacking differ modestly from those under full repacking. We also show that for the computationally manageable New York, NY, DMA the difference in payouts remains small under strategic bidding.

Despite the numerous simplifications, our simulation exercise is near the bound of what can be achieved in a reasonable amount of time. 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, followed by the Santa Barbara, CA, DMA with 2,205 strategy profiles and the San Francisco, CA, DMA with 1,701 strategy profiles. Across all 202 DMAs, the total number of strategy profiles is 52,356, each of which requires a run of the "regionalized" reverse auction for each draw of reservation values. Scaling this up by $N^s = 100$ draws of reservation values requires 5,235,600 runs. To give a sense of the computational burden, we note that those runs required a total of 23,710 CPU-days just for the 84 MHz clearing target.

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. There may be multiple equilibria, and we enumerate all of them. We discard equilibria that entail a failure at the outset (see footnote 26) as these are of little practical relevance. Because many of the remaining equilibria 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 Section 7.

7 Ownership concentration and strategic supply reduction

In describing the results of our simulation exercise, we begin with a case study of the Philadelphia, PA, DMA before turning to nationwide payouts in the reverse auction and the payouts increases from strategic supply reduction. We conclude with the efficiency losses from strategic supply reduction.

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 2 shows a sample draw of reservation values 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).[50] All panels show reservation values and

[49]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 197.17 seconds under limited repacking.

[50]WPVI-TV, the Philadelphia ABC affiliate, is a VHF station and therefore not included in Figure 2.

payouts (in $ million) in light and dark gray, respectively, on the left axis. On the right axis, we account for the broadcast volumes of the TV stations and display their bids and payouts in terms of the base clock price as rectangles and triangles, respectively. A bid is the critical value of the base clock price above which a TV station continues in the reverse auction and at or below which the TV station opts to remain on the air. We label the TV stations by their network affiliation and order them by their reservation values. Finally, we indicate multi-license ownership using symbols to distinguish between owners.

Naive bidding. Panel (a) of Figure 2 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 (labeled [+]), in particular, owns the independent station WTVE (reservation value $15.26 million) and the Youtoo America affiliate WPHY-CD (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 TV stations, is $95.02 million.

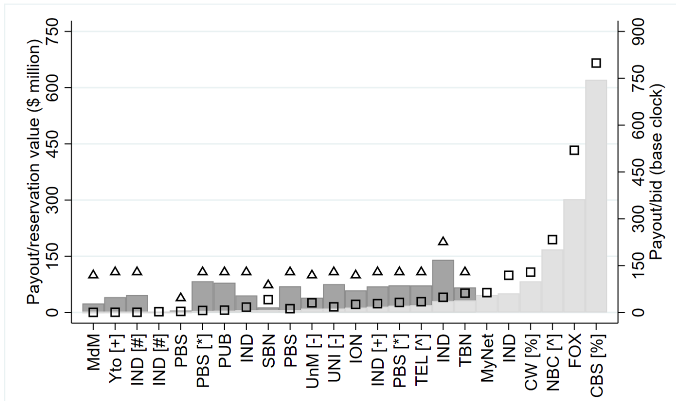
Equilibrium 1: Same number of TV stations sell. The equilibrium in panel (b) illustrates that strategic supply reduction by multi-license owners can lead to the same number of TV stations being sold as under naive bidding, but at weakly higher prices. We identify TV stations that are withheld from the reverse auction with bids of 900. In this equilibrium, NRJ withholds the Youtoo America affiliate WPHY-CD. Relative to naive bidding, NRJ thus 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 $51.76 million on the independent station WTVE, as the freezing base clock price increases from 129.34 to 225.47. Strategic supply reduction additionally increases payouts to several other TV stations that continue to bid naively Overall, the same number of TV stations sell as under naive bidding, but at weakly higher prices, and payouts in the Philadelphia, PA, DMA increase from $1004.54 million to $1543.65 million.

Equilibrium 2: More TV stations sell. The equilibrium in panel (c) highlights that strategic supply reduction can increase the number of TV stations being sold. In this equilibrium, NRJ continues to withhold the Youtoo America affiliate WPHY-CD from the reverse auction. In addition, the NJ Public Broadcasting Authority (labeled [*]) withholds the PBS affiliate WNJS, one of the two TV stations it owns in the Philadelphia, PA, DMA, and NBC (labeled [ˆ]) withholds the NBC affiliate WCAU, one of the two TV stations it owns. Nevertheless, more TV stations sell than under naive bidding: four TV stations—the CW affiliate WPSG, the My Network TV affiliate WPHL-TV, and the two independent stations WMCN-TV and WQAV-CD—sell under strategic bidding but not under naive bidding.

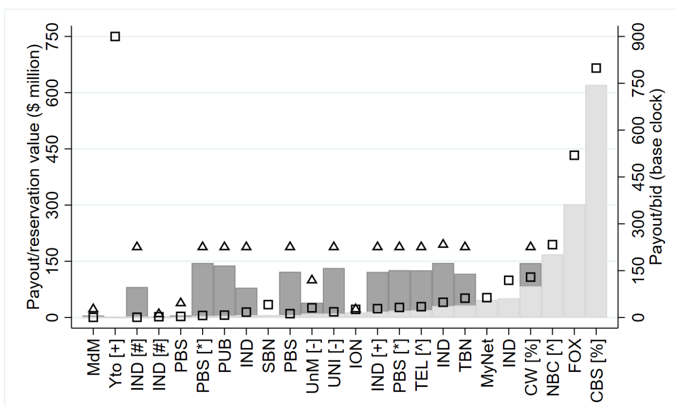
NRJ again increases its profit through strategic supply reduction. While NRJ forgoes a payout of $40.87 million and a profit of $40.64 million on WPHY-CD, it collects an additional payout and thus profit of $210.13 million on the independent station WTVE, as the freezing base clock

Figure 2: Sample outcome for Philadelphia, PA, DMA, 126 MHz clearing target

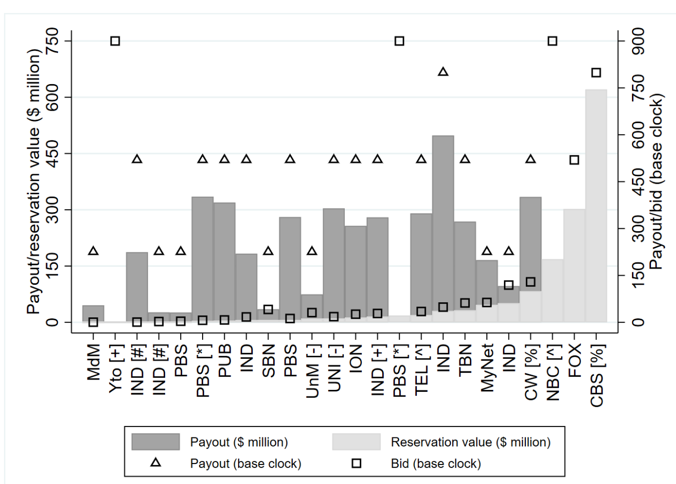
(a) Naive bidding



(b) Strategic bidding: Same number of TV stations sell



(c) Strategic bidding: More TV stations sell



price increases to 519.56. Strategic supply reduction also increases the profit of the NJ Public Broadcasting Authority and the profit of NBC. Overall, the FCC pays a total of $4,007.41 million for 19 TV stations with combined reservation values of $340.78 million.

Figure 2 illustrates the reverse auction for 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 9.416 underlying equilibria. In the subsequent analysis, we therefore repeat the above exercise for all 202 DMAs, enumerating all payout-unique equilibria and using $N^s = 100$ draws of reservation values to account for randomness.

7.2 Nationwide payouts in the reverse auction

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.[51] To do so, 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 outcome of interest.

Table 4 shows payouts to TV stations in the reverse auction under naive and strategic bidding, first nationwide and then broken down for single- and multi-license owners, for the 126 MHz clearing target at the start of the incentive auction and the 84 MHz clearing target at its conclusion.[52] On average across payout-unique equilibria and simulation draws, nationwide payouts are $22.457 billion under strategic bidding and the 126 MHz clearing target and $2.812 billion under strategic bidding and the 84 MHz clearing target. In exchange, the FCC acquires TV stations with a combined reservation value of $4.216 billion and $0.900 billion, respectively. Independent of the clearing target, strategic bidding raises nationwide payouts in the reverse auction. At the mean, strategic bidding increases nationwide payouts by $6.69 billion from $15.767 billion to $22.457 billion for the 126 MHz clearing target, an increase of 42.4%, and by $0.334 billion from $2.478 billion to $2.812 billion for the 84 MHz clearing target, an increase of 13.5%.

[51] 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 0.03% of runs of the reverse auction, corresponding to six 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 0.12% 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.

[52] In line with the regional approach described in Section 6.2, in what follows we define a multi-license owner as a firm owning more than one TV station within the focal DMA.

Table 4: 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)	2.478	2.812	2.679	2.810	2.953	13.5
	(0.360)	(0.420)	(0.403)	(0.426)	(0.454)	
Single-license owners	1.643	1.856	1.764	1.854	1.955	12.9
	(0.281)	(0.323)	(0.305)	(0.326)	(0.355)	
Multi-license owners	0.835	0.956	0.909	0.956	1.004	14.5
	(0.159)	(0.173)	(0.177)	(0.174)	(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.

The reduced scope for strategic bidding to raise nationwide payouts under the 84 MHz clearing target reflects the skewed distribution of reservation values that 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, 457.64 TV stations are acquired to meet the 126 MHz clearing target, but only 185.24 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.

The remaining rows in Table 4 break down payouts for single- and multi-license owners. The payout increase from strategic bidding for multi-license owners is 46.1% and 14.5% under the 126 MHz and 84 MHz clearing targets, respectively. As in our case study of the Philadelphia, PA, DMA in Section 7.1, 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.

As in the actual reverse auction (see Section 2), payouts are concentrated in a small number of DMAs. Under the 84 MHz clearing target, the Los Angeles, CA, DMA accounts for 37.8% of the $2.812 billion payout, followed by the New York, NY, DMA with 14.8% and the Philadelphia, PA, DMA with 11.9%. Overall, ten DMAs account for 83.3% of the $2.812 billion payout.

Decomposition of payout gains. Similar to payouts, the payout increases due to strategic bidding are concentrated in a small number of DMAs. Under the 84 MHz clearing target, the Los Angeles, CA, DMA accounts for 46.7% of the $0.334 billion gains, followed by the Philadelphia, PA, DMA with 15.3% and the New York, NY DMA with 12.6%. Overall, 10 DMAs account for 96.4% of the $0.334 billion gains.[53]

Table 5: Decomposition of payout gains from strategic bidding in 10 DMAs by type of TV station, 84 MHz clearing target

	Payout change ($ billion)				Number of TV stations			
	Overall	Always selling	Newly selling	No longer selling	Total	Always selling	Newly selling	No longer selling
Los Angeles, CA	0.156	0.127	0.051	−0.022	28	10.758	0.737	0.652
Philadelphia, PA	0.051	0.039	0.020	−0.008	24	11.264	1.163	0.386
New York, NY	0.042	0.040	0.012	−0.010	25	10.399	0.513	0.291
San Francisco, CA	0.024	0.022	0.006	−0.004	24	9.379	0.366	0.291
Washington, DC	0.016	0.014	0.006	−0.003	19	6.947	0.723	0.513
Pittsburgh, PA	0.010	0.008	0.004	−0.002	23	6.057	1.782	1.503
Chicago, IL	0.008	0.006	0.003	−0.001	21	5.764	0.215	0.066
Hartford, CT	0.007	0.008	0.002	−0.003	11	4.859	0.280	0.231
Boston, MA	0.005	0.005	0.001	−0.001	20	6.334	0.181	0.176
Burlington, VT	0.003	0.001	0.004	−0.002	11	1.720	1.691	0.420
10 DMAs	0.322	0.269	0.109	−0.056	206	73.481	7.652	4.529
Nationwide	0.334	0.277	0.120	−0.063	1670	177.719	12.729	7.521

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.

We further investigate the sources of the gains from strategic bidding in Table 5. The left panel lists the gains for the ten DMAs (column labeled "overall") under the 84 MHz clearing target, averaged across payout-unique equilibria and simulation draws, and decomposes them into the gains accruing to TV stations that sell under both naive and strategic bidding (labeled "always selling"), to TV stations that sell only under strategic bidding ("newly selling"), and to TV stations that sell only under naive bidding ("no longer selling"). Across the ten DMAs, TV stations that sell under both naive and strategic bidding account for between 20.1% and 104.6% of the payout increases due to strategic bidding. Taking the ten DMAs together, TV stations that sell under both naive and strategic bidding account for 83.5% of the $0.322 billion gains.

The right panel of Table 5 shows the number of TV stations in the ten DMAs ("total") and a

[53] 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.

Table 6: Minimum number of withdrawing TV stations and number of essential TV stations

	Strategic bidding			
	Mean	Min	Median	Max
Panel A: 126 MHz clearing target				
Minimum number of withdrawing TV stations	38.693	24.430	38.880	52.590
	(4.711)	(4.370)	(4.722)	(6.673)
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				
Minimum number of withdrawing TV stations	29.355	13.120	29.570	45.040
	(5.273)	(3.201)	(5.497)	(8.754)
Number of essential TV stations	26.305	12.160	25.900	41.260
	(4.878)	(3.110)	(5.046)	(8.584)

decomposition into the three categories.[54] Taking the ten DMAs together, 73.48 or 90.6% of the $73.48 + 7.65 = 81.13$ TV stations that sell under strategic bidding also sell under naive bidding. This suggests that in many equilibria strategic supply reduction does not significantly change the number of TV stations that sell, similar to the first equilibrium in Section 7.1. It also suggests that strategic supply reduction does not significantly change the identity of the TV stations that sell. Instead, strategic supply reduction increases the price at which these TV stations sell. 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 \$45.74 under strategic bidding. Under the 126 MHz clearing target, the respective prices are \$80.28 and \$146.46.

Bidding behavior. The results so far highlight the payout increases due to 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 TV stations that withdraw from the reverse auction in a given equilibrium is not a meaningful measure of differences in behavior. We instead count the minimum number of TV stations that withdraw from the reverse auction by overbidding $b_j = 900$ across all equilibria underlying a payout-unique equilibrium.

Of the 1,670 TV stations, 498 belong to a chain within the same DMA and can thus be part of a supply reduction strategy.[55] Table 6 shows that in comparison, the minimum number of

[54]The omitted category in this decomposition is TV stations that sell under neither naive nor strategic bidding.

[55]While we set the strategy space of TV station j to $b_j = 900$ if it is not needed (see Section 6.2), we do not consider this to be part of a supply reduction strategy.

withdrawing TV stations among these 498 TV stations is small: it amounts to 38.69 or 7.8% under the 126 MHz clearing target and to 29.36 or 5.9% under the 84 MHz clearing target, on average across payout-unique equilibria and simulation draws. Thus, withholding relatively few TV stations from the reverse auction suffices to give rise to equilibria that have significantly higher payouts than that under naive bidding.

This analysis leaves open the possibility that the equilibria underlying a payout-unique equilibrium feature a rotation cast of withdrawing TV stations. To investigate, we define a TV station to be essential to a payout-unique equilibrium 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. By construction, the number of essential TV stations cannot exceed the minimum number of withdrawing TV stations. Table 6 shows that, on average across payout-unique equilibria and simulation draws, the number of essential TV stations is not much smaller than the minimum number of withdrawing TV stations. In this sense, strategic supply reduction hinges on a small number of pivotal TV stations.

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 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 mention 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 1.14 standard deviations in the number of freezes.

We also find that the private equity firms were likely to acquire essential TV stations that are pivotal in changing equilibrium payouts. Ranking TV stations in descending order 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 13 of the top 20 TV stations. These amount to 26.7% and 39.1% of the overall 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 actual reverse auction. Specifically, NRJ relinquished two TV stations, NRJ seven TV stations, and OTA ten TV stations. As Table 7 shows, under the 84 MHz clearing target, we estimate the private equity firms to relinquish 18.68 TV stations under naive bidding on

Table 7: Private equity firms' payouts and sales of TV stations, 84 MHz clearing target

	Naive bidding		Strategic bidding		Payout increase at mean (%)
	Number TV stations sold	Payout ($ million)	Number TV stations sold	Payout ($ million)	
LocusPoint	3.03	22.927	3.34	27.617	7.3
	(1.23)	(11.659)	(1.12)	(12.316)	
NRJ	6.10	123.063	6.00	158.012	25.3
	(1.76)	(54.251)	(1.64)	(65.111)	
OTA	9.55	51.064	9.16	59.865	5.5
	(1.79)	(15.042)	(1.85)	(18.234)	

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

average across simulation draws and 18.50 TV stations under strategic bidding on average across payout-unique equilibria and simulation draws. Table 7 also shows that we estimate the private equity firms to experience sizable payout increases from strategic bidding, ranging from 5.5% to 25.3% across firms.

Model fit. As noted in Section 6.1, the noise in our estimated reservation values limits the ability of our model to predict the outcome of the actual reverse auction. 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 0.88 on average across simulation draws. By comparison, 163 UHF stations relinquished their licenses in the actual reverse auction (see Section 2), and randomly drawing 163 out of 1,670 TV stations yields a "hit rate" of 0.82.

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 these probabilities in perspective, randomly drawing 163 out of 1,670 TV stations along with their DMAs yields a hit rate of 0.56.

Yet, our model predicts higher payouts in the Los Angeles, CA, DMA than in the New York, NY, DMA under the 84 MHz clearing target and either naive or strategic bidding, whereas in the actual reverse auction, payouts were highest in the New York, NY, DMA, followed by the Los Angeles, CA, and Philadelphia, PA, DMAs.[56] Moreover, payouts in the actual reverse auction amounted to

[56]As discussed in footnote 46, we estimate the reservation value of the flagship CBS affiliate on the West Coast, KCBS-TV 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 withdrew from the auction at a price of $547 while the estimated reservation value is $33 million and WEDW withdrew at a price of $425 million while the estimated reservation value is $28 million.

Table 8: **Payouts to TV stations nationwide under realized participation**

Payouts ($ billion)	Naive bidding	Strategic bidding Mean	Min	Median	Max	Payout increase at mean (%)
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.

$10.1 billion at the 84 MHz clearing target, whereas we predict payouts of $2.812 billion on average across payout-unique equilibria and simulation draws, and 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. A large part of this gap can be traced 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. We comment on relaxing these assumptions in turn.

Reduced participation. While the FCC had initially decided not to release data on participation or bids in the reverse auction, it subsequently reversed course (see Section 2). The recently released data shows that only 898 or 53.77% of the 1,670 TV stations participated in the reverse auction. We relax the assumption of full participation and use this data to set the bid of a non-participating TV station to $b_j = 900$. Table 8 shows the resulting payouts to TV stations under naive and strategic bidding and the 84 MHz clearing target.[57] Comparing Table 8 to our main results in Table 4 highlights the importance of participation: on average across payout-unique equilibria and simulation draws, nationwide 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, is 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.

[57]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. While 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.

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.

As we detail in Online Appendix H, twelve of the 18 owners hold at least one additional license in the repacking region but outside the Philadelphia, PA, DMA. NRJ, in particular, owns WGCB-TV in the Harrisburg, PA, DMA. As an example of a multi-market strategy, we allow NRJ to bid strategically on WGCB-TV in concert with its two TV stations in the Philadelphia, PA, DMA. As a result, payouts in the Philadelphia, PA, DMA increase by 6.3% under the 84 MHz clearing target, on average across payout-unique equilibria and simulation draws, 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.

7.3 Efficiency losses from strategic bidding

There are 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 or reduces the amount of spectrum that is re-purposed from broadcast TV to mobile broadband usage. We discuss these two potential sources of efficiency losses in turn.

Taking the clearing target as given, 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.[58] Not surprisingly in light of the results in Table 5, the total reservation value of acquired TV stations under naive and strategic bidding are very similar. This reflects in part that roughly the same number of TV stations sell in the reverse auction under naive and strategic bidding, averaging across simulation draws to 185.24 under naive bidding and the 84 MHz clearing target and averaging across payout-unique equilibria and simulation draws to 190.45 under strategic bidding.[59] We thus do not find a sizable distortion from strategic bidding in the set of TV stations that relinquish their licenses in the reverse auction.

In Online Appendix I, we further argue that the reverse auction comes close to minimizing the total reservation value of acquired TV stations subject to meeting the clearing target. We extend the efficiency analysis in Newman et al. (2017) for New York, NY, to the top ten DMAs in terms of payouts in the actual reverse auction. Overall, the auction design is close to efficient,

[58] Using the estimated private reservation value of a TV station in lieu of its social value neglects consumer surplus, e.g., due to broadcast variety, to the extent that it is not appropriated by the TV station.

[59] 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.

thereby limiting the scope for further efficiency gains from re-designing the reverse auction or using altogether different mechanisms such as bilateral negotiations between the FCC and TV stations.

The possibility that strategic bidding leads to a reduction in the clearing target and the amount of spectrum that is re-purposed is more difficult to assess. First, we do not know the social value of spectrum. Second, modeling the forward auction is outside of the scope of this paper. However, we note that TV stations demanded \$40.3 billion whereas wireless carriers offered \$19.7 billion in stage 3 of the incentive auction with a clearing target of 108 MHz (see Section 2). In view of the payout increases due to strategic bidding under both the 126 MHz and the 84 MHz clearing targets in Table 4, it is doubtful that the final stage rule would have been met at the 108 MHz clearing target absent strategic supply reduction.[60]

8 Mitigating the impact of ownership concentration

In Section 7, we have shown that strategic bidding by multi-license owners causes a substantial transfer from the government—and ultimately taxpayers—to TV stations. To further illustrate the usefulness of our framework, we show that this transfer can be greatly reduced by relatively simple changes in the design of the reverse auction. First, we propose a change in the auction rules that places a restriction on the bids of multi-license owners akin to an activity rule and 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 interference between TV stations.

8.1 Restriction on multi-license owners

The discussion 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), but sets aside any legal considerations the FCC may face.

Table 9 shows how the rule change affects our main results in Table 4. The payout increase from strategic bidding is between 71% and 89% less than in Table 4, 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 TV stations.

[60] Of course, the design of the reverse auction could have been modified to accommodate additional clearing targets between 108 MHz and 84 MHz.

Table 9: 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)	2.478	2.575	2.554	2.576	2.596	3.9
	(0.360)	(0.384)	(0.384)	(0.384)	(0.386)	

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

8.2 Relaxing repacking constraints

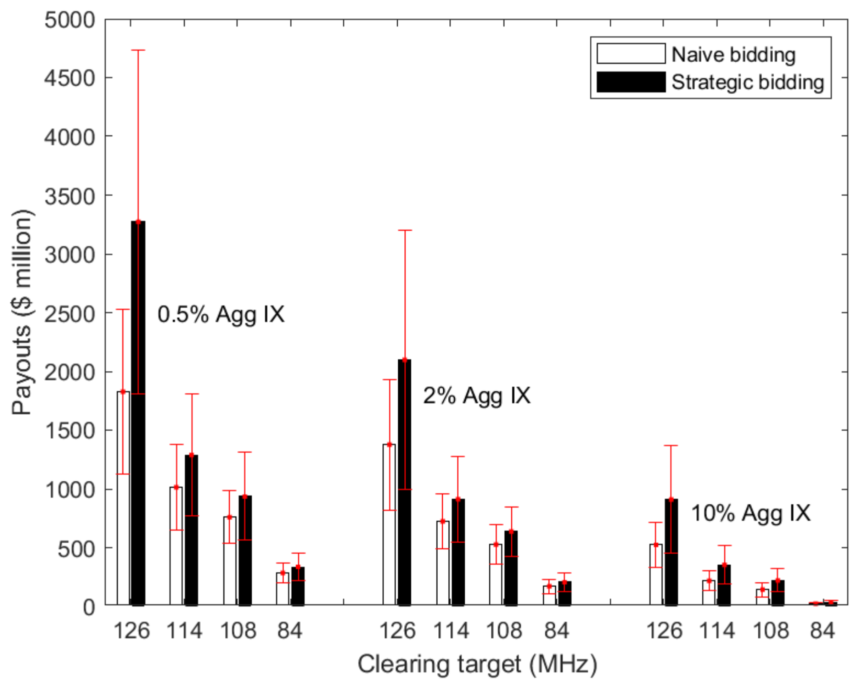
In designing the reverse auction, the FCC had to make a number of choices. One such choice is the maximum loss in population served that a TV station may suffer in the repacking process, as discussed in Section 4.2. While the FCC settled on a 0.5% interference level, the alternative, looser standards 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 twelve 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, 108 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 3, 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 3. First, in line with the nationwide results in Table 4, 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 pro-

Figure 3: Payouts to TV stations in Philadelphia, PA, DMA under alternative interference levels and clearing targets



cess 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.

9 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 outside investors as more likely to part with their TV stations than potentially "sentimental" owners.[61] At the same time, as our paper shows, ownership concentration is likely to give rise to strategic supply reduction in the reverse auction.

Using a large-scale valuation and simulation exercise, we estimate reservation values for the 1,670 auction-eligible UHF stations located outside Puerto Rico and the Virgin Islands and compare the outcome of the reverse auction under strategic bidding when we account for the ownership pattern in

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

the data with the outcome under naive bidding. Naive bidding is implied by the single-mindedness assumption that underpins the theoretical development of the reverse auction in Milgrom and Segal (2020). 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 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, the outcome of the reverse auction is sensitive to small changes in bidding behavior in that withholding relatively few TV stations suffices to give rise to equilibria that have significantly higher payouts than those under naive bidding. Fourth, strategic supply reduction has limited efficiency implications. Taking the clearing target as given, strategic supply reduction does not cause a sizable distortion in the set of TV stations that relinquish their licenses in the reverse auction. Moreover, it is doubtful that strategic supply reduction has caused a sizable reduction in the amount of spectrum that is re-purposed from broadcast TV to mobile broadband usage.

Our main results likely understate the impact of strategic supply reduction on prices and payouts to TV stations because we make several conservative assumptions. We show that moving from our baseline assumption of full participation to reduced participation substantially increases payouts. We also show that allowing strategic bidding to extend beyond market boundaries has the potential to further exacerbate payouts and payout increases due to 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 the framework we provide in two 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. In both cases, the transfer from the government—and ultimately taxpayers—to the TV stations can be greatly reduced. We view our framework as a complement to the theoretical analysis of auctions and hope that it proves useful in designing future auctions geared at re-purposing spectrum toward more efficient uses.

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Appendix

A Reservation values

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

A.1 Cash flows

Specification. We parameterize $\alpha(X_{jt};\beta)$, $RT(X_{jt};\gamma)$, and $F(X_{jt};\delta)$ in the cash flow model in equation (8) as functions of station and market characteristics X_{jt} as

$$\begin{aligned}
\alpha(X_{jt};\beta) = & \sum_{a=1}^{9} \beta_0^a 1(\mathit{Affiliation}_{jt}=a) + \beta_1 Fox_{jt}(t-2002) + \beta_2 JSA/LMA_{jt} \\
& + \sum_{s=2003}^{2012} \beta_3^s 1(t=s) + \beta_4 CompIndex_{jt} + \beta_5 WealthIndex_{jt}, \\
RT(X_{jt};\gamma) = & \exp\left(\sum_{h=1}^{3} \gamma_0^h 1(Group_{jt}^{RT}=h) + \gamma_1 \ln(PopServed_{jt}) + \gamma_2 \ln(PopServed_{jt})^2 + \gamma_3(t-2002)\right),
\end{aligned}$$

$$F(X_{jt};\delta) = \exp\left(\sum_{h=1}^{3} \delta_0^h 1(Group_{jt}^{F}=h) + \delta_1 \ln(PopServed_{jt}) + \delta_2 \ln(PopServed_{jt})^2\right),$$

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

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

In specifying $\alpha(X_{jt};\beta)$, $Affiliation_{jt}$ refers to nine of the eleven affiliations in Table S17.[62] We normalize the parameter on the indicator for Spanish-language networks to zero. We include a full set of year fixed effects and a separate time trend for Fox affiliates as their profitability grew substantially over time. We include an indicator for the TV station being part of a joint sales or local marketing agreement.[63] We account for differences in the competitive environment and demographics across DMAs using the competitiveness and wealth indices $CompIndex_{jt}$ and $WealthIndex_{jt}$.[64] In specifying $RT(X_{jt};\gamma)$ and $F(X_{jt};\delta)$, we flexibly include the DMA population

[62]We exclude any TV station affiliated with other minor networks from the estimation in line with footnote S8. 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.

[63]Under a local marketing agreement (LMA), a company operates the TV station owned by another company. Under a joint sales agreement (JSA), only certain functions are contracted, in particular advertising sales.

[64]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

and interference free population for full-power stations and low-power class-A stations, respectively. Moreover, in specifying $RT\left(X_{jt};\gamma\right)$, we use $Group_{jt}^{RT}$ to group affiliations as (1) ABC, CBS, NBC, Fox, and Warner Bros; (2) CW, My Network TV, United Paramount, and Independents; (3) Spanish-language networks. We include a time trend because retransmission fees grew rapidly. In specifying $F\left(X_{jt};\delta\right)$, we use $Group_{jt}^{F}$ to group affiliations as (1) ABC, CBS, and NBC; (2) Fox, CW, and Warner Bros; (3) My Network TV, United Paramount, Spanish-language networks, and Independents.

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. We draw $N^s = 100$ vectors of cash flow error terms $\epsilon^s = \left(\epsilon_{jt}^s\right)$, where ϵ_{jt}^s is the cash flow error term of TV station j in year t in draw s. Denote by $\overline{CF}_{gt}$, CF_{gt}^1, CF_{gt}^2, 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 $\theta = (\beta, \gamma, \delta, \sigma)$ and the vector of cash flow error terms ϵ^s in draw s. We use similar notation for the mean of the non-broadcast revenue and fixed cost distributions, replacing $\overline{CF}$ with $\overline{RT}$ and $\overline{F}$, respectively. To estimate θ, we match the moments of the predicted and actual distributions across aggregation categories and years and 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.

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.

Table A1: Cash flow parameters estimates

	Estimate
Retained share $\alpha(X_{jt}; \beta)$	
ABC	-0.0417
CBS	-0.0521
NBC	-0.0500
Fox	-0.3545
CW	-0.0680
Warner Bros	-0.0255
MyNetwork TV	-0.2648
United Paramount	-0.3252
Spanish-language networks (normalized)	0
Independent	-0.0879
Fox $\times$ Trend	0.0113
JSA/LMA	0.2892
2003	0.5563
2004	0.5355
2005	0.5074
2006	0.4948
2007	0.4611
2008	0.4302
2009	0.3735
2010	0.4501
2011	0.4635
2012	0.4881
$CompIndex_{jt}$	0.0127
$WealthIndex_{jt}$	0.0028
Non-broadcast revenue $RT(X_{jt}; \gamma)$	
Group 1	9.5292
Group 2	8.6304
Group 3	8.4692
$\ln(PopServed_{jt})$	0.4500
$\ln(PopServed_{jt})^2$	0.0116
Trend	0.1620
Fixed cost $F(X_{jt}; \delta)$	
Group 1	1.4670
Group 2	0.6279
Group 3	0.2943
$\ln(PopServed_{jt})$	2.9244
$\ln(PopServed_{jt})^2$	-0.1413
Standard deviation σ	0.6896

Results. Table A1 reports the parameter estimates $\hat{\theta}$. We provide further details on predicted values and goodness of fit in Online Appendix E.1.

A.2 Multiples

Data. BIA records 659 transactions in the eleven years from 2003 to 2013 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 TV 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 TV stations with widely varying cash flows to facilitate allocating the purchase price in proportion to the population covered by the included TV stations. Lastly, we exclude four transactions with a cash flow multiple in excess of 250. This leaves us with a sample of 230 transactions between 2003 and 2012 based on cash flow.

In identifying transactions based on stick value, we include transactions for dark stations, for TV stations with negative predicted cash flows, and for TV 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 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 (5), 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 (6) and (7).

Specification and estimation. For cash flow transactions, we regress the log of the multiple on station, owner, and market characteristics using the specification:

$$\ln Multiple_{jt}^{CF} = \beta^{CF} X_{jt} + \epsilon_{jt}^{CF}. \tag{A1}$$

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 S17 in Online Appendix B.1. 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 specification:

$$\ln Multiple_{jt}^{Stick} = \beta^{Stick} X_{jt} + \epsilon_{jt}^{Stick}. \tag{A2}$$

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 LPTV fixed effect, a full-power fixed effect, a fixed effect for satellite stations, and a full set of year fixed effects.

Table A2: 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)		
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	

Results. Table A2 reports parameter estimates $\hat{\beta}^{CF}$and $\hat{\beta}^{Stick}$. The adjusted R^2 is 0.82 for the specifications in equations (A1) and (A2), suggesting that they fit the data well. We set $\epsilon_{jt}^{CF} = \epsilon_{jt}^{Stick} = 0$ to predict. We provide further details in Online Appendix E.2.

Online Appendix

A Additional analysis of the model

In this appendix, we provide additional analysis of the model in Section 3.

A.1 Set of equilibria

Example in Section 3.1 with joint ownership. We derive the set of equilibria for the example in Section 3.1. The profit of firm 1 owning TV stations 1 and 3 is

$$\pi_1(b_1,b_2,b_3)=\begin{cases} 0 & \text{if} \quad \min\{b_1,b_2\}\geq 900 \\ & \quad \vee \min\{b_1,b_3\}\geq 900 \\ & \quad \vee \min\{b_2,b_3\}\geq 900, \\ \min\{b_1,900\}-300 & \text{if} \quad b_1>\max\{b_2,b_3\}, \\ 2\min\{b_2,900\}-400 & \text{if} \quad b_2>\max\{b_1,b_3\}, \\ \min\{b_3,900\}-100 & \text{if} \quad b_3>\max\{b_1,b_2\}, \\ \frac{1}{2}(2b_2-400)+\frac{1}{2}(b_2-300) & \text{if} \quad b_1=b_2>b_3, \\ \frac{1}{2}(b_1-100)+\frac{1}{2}(b_1-300) & \text{if} \quad b_1=b_3>b_2, \\ \frac{1}{2}(2b_2-400)+\frac{1}{2}(b_2-100) & \text{if} \quad b_2=b_3>b_1, \\ \frac{1}{3}(2b_2-400)+\frac{1}{3}(b_2-100)+\frac{1}{3}(b_2-300) & \text{if} \quad b_1=b_2=b_3>0, \\ -400 & \text{if} \quad b_1=b_2=b_3=0 \end{cases} \tag{S1}$$

and the profit of firm 2 owning TV station 2 is

$$\pi_2(b_1,b_2,b_3)=\begin{cases} 0 & \text{if} \quad \min\{b_1,b_2\}\geq 900 \vee \min\{b_1,b_3\}\geq 900 \\ & \quad \vee \min\{b_2,b_3\}\geq 900, \\ 0 & \text{if} \quad b_2>\max\{b_1,b_3\}, \\ \min\{\max\{b_1,b_3\},900\}-500 & \text{if} \quad b_2<\max\{b_1,b_3\}, \\ \frac{1}{2}(\max\{b_1,b_3\}-500) & \text{if} \quad b_2=\max\{b_1,b_3\}>\min\{b_1,b_3\}, \\ \frac{2}{3}(b_1-500) & \text{if} \quad b_1=b_2=b_3>0, \\ -500 & \text{if} \quad b_1=b_2=b_3=0, \end{cases}$$

where we again assume that the relevant case is given by the first applicable if statement.

In Tables S1-S3, we again divide the strategy spaces of firms 1 and 2 as needed to either show that there is no profitable deviation for any firm or give an example of a profitable deviation. Combining the cells marked with ✓, the set of equilibria is as stated in equation (3).

Table S1: $b_2 \in [0, 600)$

$b_1 \setminus b_3$	$[0, b_2)$	b_2	$(b_2, 900)$	$[900, \infty)$
$[0, b_2)$	$(b_1, b_3) = (0, 900)$	$(b_1, b_3) = (0, 900)$	$(b_1, b_3) = (0, 900)$	✓
b_2	$(b_1, b_3) = (0, 900)$	$(b_1, b_3) = (0, 900)$	$(b_1, b_3) = (0, 900)$	✓
$(b_2, 900)$	$(b_1, b_3) = (0, 900)$	$(b_1, b_3) = (0, 900)$	$(b_1, b_3) = (0, 900)$	✓
$[900, \infty)$	$(b_1, b_3) = (0, 900)$	$(b_1, b_3) = (0, 900)$	$(b_1, b_3) = (0, 900)$	$(b_1, b_3) = (0, 900)$

Table S2: $b_2 = 600$

$b_1 \setminus b_3$	$[0, 500]$	$(500, 600)$	600	$(600, 900)$	$[900, \infty)$
$[0, 500]$	✓	$b_2 = 0$	$b_2 = 0$	$(b_1, b_3) = (0, 900)$	✓
$(500, 600)$	$b_2 = 0$	$b_2 = 0$	$b_2 = 0$	$(b_1, b_3) = (0, 900)$	✓
600	$b_2 = 0$	$b_2 = 0$	$b_2 = 0$	$(b_1, b_3) = (0, 900)$	✓
$(600, 900)$	$(b_1, b_3) = (0, 0)$	$(b_1, b_3) = (0, 0)$	$(b_1, b_3) = (0, 0)$	$(b_1, b_3) = (0, 900)$	✓
$[900, \infty)$	$(b_1, b_3) = (0, 0)$	$(b_1, b_3) = (0, 0)$	$(b_1, b_3) = (0, 0)$	$(b_1, b_3) = (0, 900)$	$(b_1, b_3) = (0, 900)$

Table S3: $b_2 \in (600, \infty)$

$b_1 \setminus b_3$	$[0, 500]$	$(500, b_2)$	b_2	$(b_2, 900)$	$[900, \infty)$
$[0, 500]$	✓	$b_2 = 0$	$b_2 = 0$	$(b_1, b_3) = (0, 0)$	$(b_1, b_3) = (0, 0)$
$(500, b_2)$	$b_2 = 0$	$b_2 = 0$	$b_2 = 0$	$(b_1, b_3) = (0, 0)$	$(b_1, b_3) = (0, 0)$
b_2	$b_2 = 0$	$b_2 = 0$	$b_2 = 0$	$(b_1, b_3) = (0, 0)$	$(b_1, b_3) = (0, 0)$
$(b_2, 900)$	$(b_1, b_3) = (0, 0)$	$(b_1, b_3) = (0, 0)$	$(b_1, b_3) = (0, 0)$	$(b_1, b_3) = (0, 0)$	$(b_1, b_3) = (0, 0)$
$[900, \infty)$	$(b_1, b_3) = (0, 0)$	$(b_1, b_3) = (0, 0)$	$(b_1, b_3) = (0, 0)$	$(b_1, b_3) = (0, 0)$	$(b_1, b_3) = (0, 0)$

Example in Section 3.1 imposing independently owned TV stations. We derive the set of equilibria for the example in Section 3.1 whilst imposing that all TV stations are independently owned. Assuming a random tie-breaking rule for bids above 0 and below 900 in line with footnote 26, the profit of TV station 1 is

$$\pi_1(b_1, b_2, b_3) = \begin{cases} 0 & \text{if} \quad \min\{b_1, b_2\} \geq 900 \vee \min\{b_1, b_3\} \geq 900 \\ & \qquad \vee \min\{b_2, b_3\} \geq 900, \\ 0 & \text{if} \quad b_1 > \max\{b_2, b_3\}, \\ \min\{\max\{b_2, b_3\}, 900\} - 100 & \text{if} \quad b_1 < \max\{b_2, b_3\}, \\ \frac{1}{2}(\max\{b_2, b_3\} - 100) & \text{if} \quad b_1 = \max\{b_2, b_3\} > \min\{b_2, b_3\}, \\ \frac{2}{3}(b_2 - 100) & \text{if} \quad b_1 = b_2 = b_3 > 0, \\ -100 & \text{if} \quad b_1 = b_2 = b_3 = 0, \end{cases}$$

where we assume that the relevant case is given by the first applicable if statement. In particular, the first if statement covers the case where the reverse auction fails at the outset because at least two TV stations bid 900 or more. Consequently, in the subsequent if statements at most one TV station bids 900 or more. In the second if statement, TV station 1 is first to opt to remain on the air. In the third if statement, TV station 1 is frozen as either TV station 2 or 3 is first to opt to remain on the air. The remaining if statements cover ties. The profits of the remaining TV stations are analogous.

In Tables S4-S10, we divide the strategy space of TV station 2 into eight regions, namely $[0,100)$, 100, $(100,300)$, 300, $(300,500)$, 500, $(500,900)$, and $[900,\infty)$. We further divide the strategy spaces of TV stations 1 and 3 as needed to either show that there is no profitable deviation for any TV station (indicated by ✓ in the respective cell) or give an example of a profitable deviation.[S1] Combining the cells marked with ✓, the set of equilibria is

$$\begin{aligned}
&\left\{(b_1,b_2,b_3)\in[0,\infty)^3|b_1\geq 500, b_2\leq 100, b_3\leq 100\right\}\\
&\cup\left\{(b_1,b_2,b_3)\in[0,\infty)^3|b_1\leq 300, b_2\leq 300, b_3\geq 500\right\}\\
&\cup\left\{(b_1,b_2,b_3)\in[0,\infty)^3|\max\{b_1,b_3\}< b_2, 300\leq b_2\leq 500\right\}\\
&\cup\left\{(b_1,b_2,b_3)\in[0,\infty)^3|\max\{b_1,b_3\}\leq 500, b_2> 500\right\}\\
&\cup\left\{(b_1,b_2,b_3)\in[0,\infty)^3|b_1\geq 900, b_2\geq 900, b_3\geq 900\right\}.
\end{aligned} \tag{S2}$$

Table S4: $b_2 \in [0,100]$

$b_1 \setminus b_3$	$[0,b_2)$	$[b_2,100]$	$(100,500)$	$[500,\infty)$
$[0,b_2)$	$b_3=900$	$b_2=900$	$b_2=900$	✓
$[b_2,300]$	$b_2=900$	$b_2=900$	$b_2=900$	✓
$(300,500)$	$b_2=900$	$b_2=900$	$b_2=900$	$b_3=0$
$[500,\infty)$	✓	✓	$b_1=0$	$\max\{b_1,b_3\}=0$

Table S5: $b_2 \in (100,300)$

$b_1 \setminus b_3$	$[0,b_2)$	$[b_2,500)$	$[500,\infty)$
$[0,b_2)$	$b_3=900$	$b_2=900$	✓
$[b_2,300]$	$b_2=900$	$b_2=900$	✓
$(300,500)$	$b_2=900$	$b_2=900$	$b_3=0$
$[500,\infty)$	$b_1=0$	$b_1=0$	$\max\{b_1,b_3\}=0$

Table S6: $b_2 = 300$

$b_1 \setminus b_3$	$[0,300)$	$[300,500)$	$[500,\infty)$
$[0,300)$	✓	$b_2=900$	✓
300	$b_2=900$	$b_2=900$	✓
$(300,500)$	$b_2=900$	$b_2=900$	$b_3=0$
$[500,\infty)$	$b_1=0$	$b_1=0$	$\max\{b_1,b_3\}=0$

[S1]The notation $\max\{b_1,b_3\}=0$ in Table S4 means that the TV station with the higher bid has a profitable deviation to zero, and similarly for the remaining tables.

Table S7: $b_2 \in (300, 500)$

$b_1 \setminus b_3$	$[0, b_2)$	$[b_2, 500)$	$[500, \infty)$
$[0, b_2)$	✓	$b_2 = 900$	$b_3 = 0$
$[b_2, 500)$	$b_2 = 900$	$b_2 = 900$	$b_3 = 0$
$[500, \infty)$	$b_1 = 0$	$b_1 = 0$	$\max\{b_1, b_3\} = 0$

Table S8: $b_2 = 500$

$b_1 \setminus b_3$	$[0, 500)$	$[500, \infty)$
$[0, 500)$	✓	$b_3 = 0$
$[500, \infty)$	$b_1 = 0$	$\max\{b_1, b_3\} = 0$

Table S9: $b_2 \in (500, 900)$

$b_1 \setminus b_3$	$[0, 500]$	$(500, b_2]$	(b_2, ∞)
$[0, 500]$	✓	$b_2 = 0$	$b_3 = 0$
$(500, b_2]$	$b_2 = 0$	$b_2 = 0$	$b_3 = 0$
(b_2, ∞)	$b_1 = 0$	$b_1 = 0$	$\max\{b_1, b_3\} = 0$

Table S10: $b_2 \in [900, \infty)$

$b_1 \setminus b_3$	$[0, 500]$	$(500, 900)$	$[900, \infty)$
$[0, 500]$	✓	$b_2 = 0$	$b_2 = 0$
$(500, 900)$	$b_2 = 0$	$b_2 = 0$	$b_2 = 0$
$[900, \infty)$	$b_2 = 0$	$b_2 = 0$	✓

Example in Section 3.1 with different reservation values. We derive the set of equilibria for the example in Section 3.1 whilst replacing the reservation value of TV station 2 by $v_2 = 700$. We came back to this variant of the example in Online Appendix A.3. The profit of firm 1 owning TV stations 1 and 3 is

$$\pi_1(b_1, b_2, b_3) = \begin{cases} 0 & \text{if} \quad \min\{b_1, b_2\} \geq 900 \\ & \quad \vee \min\{b_1, b_3\} \geq 900 \\ & \quad \vee \min\{b_2, b_3\} \geq 900, \\ \min\{b_1, 900\} - 300 & \text{if} \quad b_1 > \max\{b_2, b_3\}, \\ 2\min\{b_2, 900\} - 400 & \text{if} \quad b_2 > \max\{b_1, b_3\}, \\ \min\{b_3, 900\} - 100 & \text{if} \quad b_3 > \max\{b_1, b_2\}, \\ \frac{1}{2}(2b_2 - 400) + \frac{1}{2}(b_2 - 300) & \text{if} \quad b_1 = b_2 > b_3, \\ \frac{1}{2}(b_1 - 100) + \frac{1}{2}(b_1 - 300) & \text{if} \quad b_1 = b_3 > b_2, \\ \frac{1}{2}(2b_2 - 400) + \frac{1}{2}(b_2 - 100) & \text{if} \quad b_2 = b_3 > b_1, \\ \frac{1}{3}(2b_2 - 400) + \frac{1}{3}(b_2 - 100) + \frac{1}{3}(b_2 - 300) & \text{if} \quad b_1 = b_2 = b_3 > 0, \\ -400 & \text{if} \quad b_1 = b_2 = b_3 = 0 \end{cases} \tag{S3}$$

and the profit of firm 2 owning TV station 2 is

$$\pi_2(b_1,b_2,b_3)=\begin{cases} 0 & \text{if} \quad \min\{b_1,b_2\}\geq 900 \vee \min\{b_1,b_3\}\geq 900 \\ & \qquad \vee \min\{b_2,b_3\}\geq 900, \\ 0 & \text{if} \quad b_2>\max\{b_1,b_3\}, \\ \min\{\max\{b_1,b_3\},900\}-700 & \text{if} \quad b_2<\max\{b_1,b_3\}, \\ \frac{1}{2}(\max\{b_1,b_3\}-700) & \text{if} \quad b_2=\max\{b_1,b_3\}>\min\{b_1,b_3\}, \\ \frac{2}{3}(b_1-700) & \text{if} \quad b_1=b_2=b_3>0, \\ -700 & \text{if} \quad b_1=b_2=b_3=0, \end{cases}$$

where we again assume that the relevant case is given by the first applicable if statement.

In Tables S11-S14, we again divide the strategy spaces of firms 1 and 2 as needed to either show that there is no profitable deviation for any firm or give an example of a profitable deviation. Combining the cells marked with ✓, the set of equilibria is

$$\begin{gathered}\left\{(b_1,b_2,b_3)\in[0,\infty)^3|b_1<900,b_2\leq 600,b_3\geq 900\right\} \\ \cup\left\{(b_1,b_2,b_3)\in[0,\infty)^3|b_1\leq 700,b_2>700,b_3\leq 700\right\} \\ \cup\left\{(b_1,b_2,b_3)\in[0,\infty)^3|\max\{b_1,b_3\}<b_2,600\leq b_2\leq 700\right\}.\end{gathered}$$

Note that firm 1 never bids $b_3=900$ as long as firm 2 truthfully bids $b_2=700$.

Table S11: $b_2\in[0,600)$

$b_1 \setminus b_3$	$[0,b_2)$	b_2	$(b_2,900)$	$[900,\infty)$
$[0,b_2)$	$(b_1,b_3)=(0,900)$	$(b_1,b_3)=(0,900)$	$(b_1,b_3)=(0,900)$	✓
b_2	$(b_1,b_3)=(0,900)$	$(b_1,b_3)=(0,900)$	$(b_1,b_3)=(0,900)$	✓
$(b_2,900)$	$(b_1,b_3)=(0,900)$	$(b_1,b_3)=(0,900)$	$(b_1,b_3)=(0,900)$	✓
$[900,\infty)$	$(b_1,b_3)=(0,900)$	$(b_1,b_3)=(0,900)$	$(b_1,b_3)=(0,900)$	$(b_1,b_3)=(0,900)$

Table S12: $b_2=600$

$b_1 \setminus b_3$	$[0,600)$	$[600,900)$	$[900,\infty)$
$[0,600)$	✓	$(b_1,b_3)=(0,0)$	✓
$[600,900)$	$(b_1,b_3)=(0,0)$	$(b_1,b_3)=(0,0)$	✓
$[900,\infty)$	$(b_1,b_3)=(0,0)$	$(b_1,b_3)=(0,0)$	$(b_1,b_3)=(0,0)$

Table S13: $b_2\in(600,700]$

$b_1 \setminus b_3$	$[0,b_2)$	$[b_2,\infty)$
$[0,b_2)$	✓	$(b_1,b_3)=(0,0)$
$[b_2,\infty)$	$(b_1,b_3)=(0,0)$	$(b_1,b_3)=(0,0)$

Table S14: $b_2 \in (700, \infty)$

$b_1 \setminus b_3$	$[0, 700]$	$(700, b_2)$	$[b_2, \infty)$
$[0, 700]$	✓	$b_2 = 0$	$(b_1, b_3) = (0, 0)$
$(700, b_2)$	$b_2 = 0$	$b_2 = 0$	$(b_1, b_3) = (0, 0)$
$[b_2, \infty)$	$(b_1, b_3) = (0, 0)$	$(b_1, b_3) = (0, 0)$	$(b_1, b_3) = (0, 0)$

A.2 Overbidding and underbidding

We supplement the notation in Section 3 as follows: Let $Y_\tau \subseteq A_\tau$ 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 the TV stations that have previously withdrawn and require channel assignments. Let $Z_\tau = \{j' \in A_\tau \setminus Y_\tau | S(I_{\tau+1} \cup \{j'\}, R) = 0\} \subseteq A_\tau$ 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. In round $\tau + 1$, the set of frozen stations is thus $F_{\tau+1} = F_\tau \cup Z_\tau$ and the set of active stations is $A_{\tau+1} = A_\tau \setminus (Y_\tau \cup Z_\tau)$.

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.

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 example 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:

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.[S2] 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 $\tilde{b}_j \leq b_j$.*

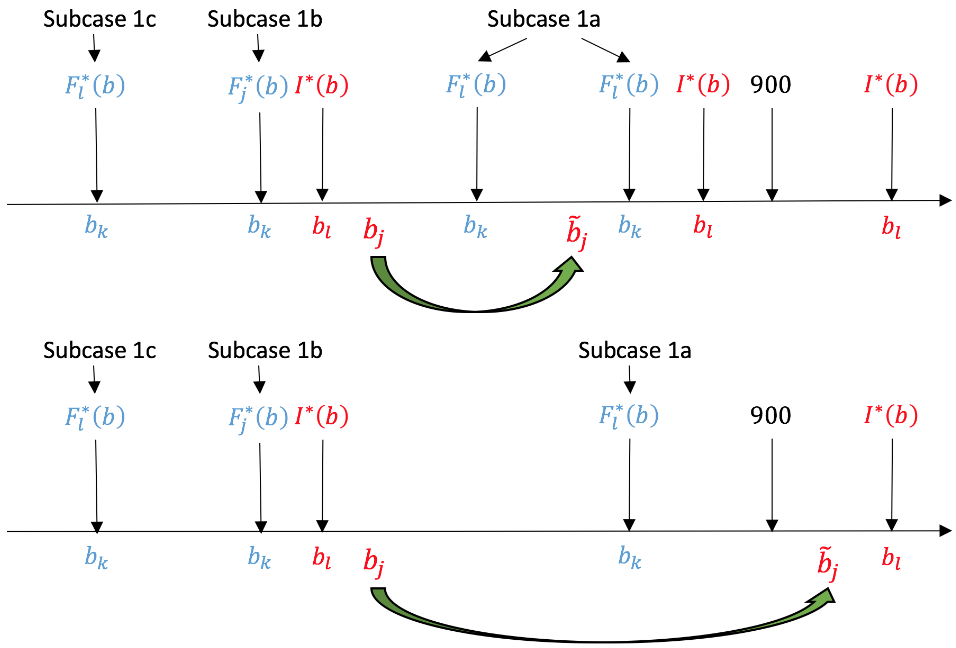
Proof. Because $j \in F^*(b)$, it must be that $j \in F_l^*(b)$ for some TV station l with $b_l > b_j$, i.e., TV station l freezes TV station j under the vector of bids b. Note that $j \in F_l^*(\tilde{b}_j, b_{-j})$ for all $\tilde{b}_j \leq b_j$ and thus $F_j^*(b) = F_j^*(\tilde{b}_j, b_{-j}) = \emptyset$, 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. $\square$

[S2] 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 S1: Case 1 and subcases in proof of Lemma 4



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 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 S1 illustrates the possible subcases.

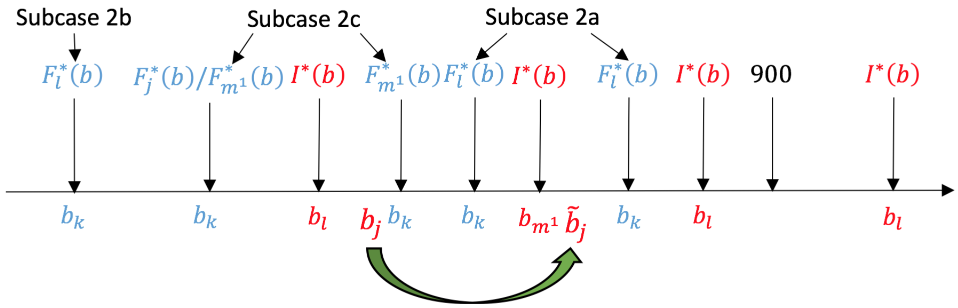
Subcase 1a: If $b_j < b_k$, then $k \in F_l^*(b)$ for some TV station l with $b_l \geq \widetilde{b}_j$. Thus $k \in F_l^*(\widetilde{b}_j, b_{-j}) \cup F_1(\widetilde{b}_j, b_{-j})$ and $PO_k(b) = P_{\tau(l)}\varphi_k = PO_k(\widetilde{b}_j, b_{-j})$.

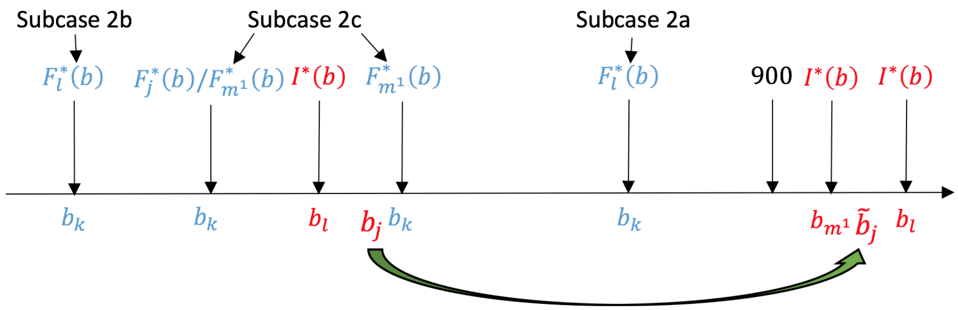
Subcase 1b: If $b_k < b_j$ and $k \in F_j^*(b)$, then $k \in F_j^*(\widetilde{b}_j, b_{-j}) \cup F_1(\widetilde{b}_j, b_{-j})$ and $PO_k(b) = P_{\tau(j)}\varphi_k < PO_k(\widetilde{b}_j, b_{-j})$.

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

Figure S2: Case 2 and subcases in proof of Lemma 4





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 S2 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 $PO_k(b) = P_{\tau(l)}\varphi_k = PO_k(b_{m^1} + \epsilon, b_{-j})$.

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 $\pi_i(b) > \pi_i(s_j, b_{-j})$. □

A.3 Incomplete 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 the example in Section 3.1 as a game of incomplete information. We assume that the reservation value v_j of TV station j is privately known to its owner and specify another firm's belief about the reservation value of TV station j to be $\tilde{v}_j \sim N(v_j, \sigma^2)$, independent across TV stations.

The game of incomplete information gives rise to bidding functions, rather than bids, that depend on beliefs. As beliefs depend on σ, note that as σ goes to zero, beliefs collapse to the true reservation values. In this way, we are able to ascertain the relationship between bidding functions under the game of incomplete information and bids under the game of complete information. In the game of incomplete information, let $b_1(v_1, v_3, \sigma) \geq 0$ and $b_3(v_1, v_3, \sigma) \geq 0$ be the bidding functions of TV stations 1 and 3 that are owned by firm 1 and $b_2(v_2, \sigma) \geq 0$ the bidding function of TV station 2 that is owned by firm 2. In what follows, we characterize the bidding functions as $\sigma \to 0^+$. We show that firm 1 always bids $b_1 < b_3$. Its expected profit depends solely on b_3 and, as $\sigma \to 0^+$, closely resembles its profit under complete information. Moreover, for a wide range of values of σ, $b_3(100, 300, \sigma)$ is arbitrarily close to (but different from) $b_3 = 900$. Close to extreme overbidding thus arises in the game of incomplete information. In a variant of the example, we also show that close to extreme overbidding arises in the game of incomplete information when σ is large. In contrast, extreme overbidding does not arise in the game of complete information. Taken together, these results suggest that our notion of strategic supply reduction in settings with jointly owned TV stations extends beyond complete information.

To recast the example in Section 3.1 as a game of incomplete information, note that expected

Table S15: Possible bid configurations

Bid configuration	TV station 1 $\Pr(1 \in F^*(b))$	$PO_1(b)$	TV station 2 $\Pr(2 \in F^*(b))$	$PO_2(b)$	TV station 3 $\Pr(3 \in F^*(b))$	$PO_3(b)$
$\min\{b_1, b_2\} = 900$ $\vee \min\{b_1, b_3\} = 900$ $\vee \min\{b_2, b_3\} = 900$	0	0	0	0	0	0
$b_1 > \max\{b_2, b_3\}$	0	0	1	b_1	1	b_1
$b_2 > \max\{b_1, b_3\}$	1	b_2	0	0	1	b_2
$b_3 > \max\{b_1, b_2\}$	1	b_3	1	b_3	0	0
$900 > b_1 = b_2 > b_3$	$\frac{1}{2}$	$b_1 \vee 0$	$\frac{1}{2}$	$b_1 \vee 0$	1	b_1
$900 > b_1 = b_3 > b_2$	$\frac{1}{2}$	$b_1 \vee 0$	1	b_1	$\frac{1}{2}$	$b_1 \vee 0$
$900 > b_2 = b_3 > b_1$	1	b_2	$\frac{1}{2}$	$b_2 \vee 0$	$\frac{1}{2}$	$b_2 \vee 0$
$900 > b_1 = b_2 = b_3 > 0$	$\frac{2}{3}$	$b_1 \vee 0$	$\frac{2}{3}$	$b_1 \vee 0$	$\frac{2}{3}$	$b_1 \vee 0$
$b_1 = b_2 = b_3 = 0$	1	0	1	0	1	0

profit of firm 1 if it bids $b_1 \geq 0$ and $b_3 \geq 0$ is

$$\begin{aligned} E\pi_1(b_1, b_3; v_1, v_3, \sigma) &= \int_{\tilde{v}_2} (PO_1(b_1, b_2(\tilde{v}_2, \sigma), b_3) - v_1)\, 1\left(1 \in F^*(b_1, b_2(\tilde{v}_2, \sigma), b_3)\right) \\ &\quad + (PO_3(b_1, b_2(\tilde{v}_2, \sigma), b_3) - v_3)\, 1\left(3 \in F^*(b_1, b_2(\tilde{v}_2, \sigma), b_3)\right) d\Phi_2(\tilde{v}_2), \end{aligned}$$

where $1(\cdot)$ is the indicator function and $\tilde{v}_2$ is distributed according to the cumulative distribution function $\Phi_2(\tilde{v}_2) = \Phi\left(\frac{\tilde{v}_2 - v_2}{\sigma}\right)$ with $\Phi(\cdot)$ being the standard normal cumulative distribution function. As firm 1 bids optimally, the bidding functions are given by $(b_1(v_1, v_3, \sigma), b_3(v_1, v_3, \sigma)) = \arg\max_{b_1, b_3 \geq 0} E\pi_1(b_1, b_3; v_1, v_3, \sigma)$. The expected profit of firm 2 if it bids $b_2 \geq 0$ is

$$\begin{aligned} E\pi_2(b_2; v_2, \sigma) &= \int_{\tilde{v}_1} \int_{\tilde{v}_3} (PO_2(b_1(\tilde{v}_1, \tilde{v}_3, \sigma), b_2, b_3(\tilde{v}_1, \tilde{v}_3, \sigma)) - v_2) \\ &\quad \cdot 1\left(2 \in F^*(b_1(\tilde{v}_1, \tilde{v}_3, \sigma), b_2, b_3(\tilde{v}_1, \tilde{v}_3, \sigma))\right) d\Phi_3(\tilde{v}_3) d\Phi_1(\tilde{v}_1). \end{aligned}$$

As firm 2 bids optimally, the bidding function is given by $b_2(v_2, \sigma) = \arg\max_{b_2 \geq 0} E\pi_2(b_2; v_2, \sigma)$.

In the interest of simplicity, we restrict $b_j \leq 900$ and consider the nine possible bid configurations in Table S15.[S3] We determine $F^*(b)$ and $PO_j(b)$ from the bid configuration along with the specification of $S(X, R)$ in equation (2), assuming a random tie-breaking rule for bids above 0 and below 900 in line with footnote 26. The expected profit of firm 1 if it bids $b_1 \in [0, 900]$ and

[S3] While restricting $b_j \leq 900$ restricts the set of equilibria, it does not restrict the payouts to TV stations associated with these equilibria.

$b_3 \in [0, 900]$ is

$$
\begin{aligned}
E\pi_1(b_1, b_3; v_1, v_3, \sigma) \;\; = \;\; & \int_{\tilde{v}_2} (b_1 - v_3)\, 1\left(b_1 > \max\left\{b_2(\tilde{v}_2, \sigma), b_3\right\}\right) \\
& + (2b_2(\tilde{v}_2, \sigma) - v_1 - v_3)\, 1\left(b_2(\tilde{v}_2, \sigma) > \max\left\{b_1, b_3\right\}\right) \\
& + (b_3 - v_1)\, 1\left(b_3 > \max\left\{b_1, b_2(\tilde{v}_2, \sigma)\right\}\right) \\
& + \left(\frac{1}{2}(b_3 - v_1) + \frac{1}{2}(b_1 - v_3)\right) 1\left(900 > b_1 = b_3 > b_2(\tilde{v}_2, \sigma)\right) \\
& - (v_1 + v_3)\, 1\left(b_1 = b_2(\tilde{v}_2, \sigma) = b_3 = 0\right) d\Phi_2(\tilde{v}_2),
\end{aligned}
$$

where we anticipate that in equilibrium firm 2's bid does not have mass points above 0 and below 900 and therefore, from firm 1's perspective, cannot tie with firm 1's bids in this range.

The expected profit of firm 2 if it bids $b_2 \in [0, 900]$ is

$$
\begin{aligned}
E\pi_2(b_2; v_2, \sigma) \;\; = \;\; & \int_{\tilde{v}_1}\int_{\tilde{v}_3} (b_1(\tilde{v}_1, \tilde{v}_3, \sigma) - v_2)\, 1\left(b_1(\tilde{v}_1, \tilde{v}_3, \sigma) > \max\left\{b_2, b_3(\tilde{v}_1, \tilde{v}_3, \sigma)\right\}\right) \\
& + (b_3(\tilde{v}_1, \tilde{v}_3, \sigma) - v_2)\, 1\left(b_3(\tilde{v}_1, \tilde{v}_3, \sigma) > \max\left\{b_1(\tilde{v}_1, \tilde{v}_3, \sigma), b_2\right\}\right) \\
& + \frac{1}{2}(b_1(\tilde{v}_1, \tilde{v}_3, \sigma) - v_2)\, 1\left(900 > b_1(\tilde{v}_1, \tilde{v}_3, \sigma) = b_2 > b_3(\tilde{v}_1, \tilde{v}_3, \sigma)\right) \\
& + (b_1(\tilde{v}_1, \tilde{v}_3, \sigma) - v_2)\, 1\left(900 > b_1(\tilde{v}_1, \tilde{v}_3, \sigma) = b_3(\tilde{v}_1, \tilde{v}_3, \sigma) > b_2\right) \\
& + \frac{1}{2}(b_3(\tilde{v}_1, \tilde{v}, \sigma_3) - v_2)\, 1\left(900 > b_2 = b_3(\tilde{v}_1, \tilde{v}_3, \sigma) > b_1(\tilde{v}_1, \tilde{v}_3, \sigma)\right) \\
& + \frac{2}{3}(b_1(\tilde{v}_1, \tilde{v}_3, \sigma) - v_2)\, 1\left(900 > b_1(\tilde{v}_1, \tilde{v}_3, \sigma) = b_2 = b_3(\tilde{v}_1, \tilde{v}_3, \sigma) > 0\right) \\
& - v_2 1\left(b_1(\tilde{v}_1, \tilde{v}_3, \sigma) = b_2 = b_3(\tilde{v}_1, \tilde{v}_3, \sigma) = 0\right) d\Phi_3(\tilde{v}_3) d\Phi_1(\tilde{v}_1).
\end{aligned}
$$

Inspection of the expected profit of firm 2 almost immediately yields

Proposition 5. *Truthful bidding* $b_2(v_2, \sigma) = \max\left\{\min\left\{v_2, 900\right\}, 0\right\}$ *is a dominant strategy for firm 2.*

Proof. We show that for any given values of $b_1(\tilde{v}_1, \tilde{v}_3, \sigma)$ and $b_3(\tilde{v}_1, \tilde{v}_3, \sigma)$, firm 2 cannot do better than bid $b_2(v_2, \sigma) = \max\left\{\min\left\{v_2, 900\right\}, 0\right\}$. We proceed by enumerating the different possible cases for $b_1(\tilde{v}_1, \tilde{v}_3, \sigma)$, $b_3(\tilde{v}_1, \tilde{v}_3, \sigma)$, and v_2. We restrict attention to cases where $b_1(\tilde{v}_1, \tilde{v}_3, \sigma) \geq b_3(\tilde{v}_1, \tilde{v}_3, \sigma)$ because cases where $b_1(\tilde{v}_1, \tilde{v}_3, \sigma) \leq b_3(\tilde{v}_1, \tilde{v}_3, \sigma)$ are analogous. For each case, Table S16 lists the best response of firm 2. A blank cell indicates that the case cannot arise. As can be seen from Table S16, the best response contains $\max\left\{\min\left\{v_2, 900\right\}, 0\right\}$ for each case, thereby establishing the proposition.

Table S16: Best response of firm 2

	(1) $v_2 > 900$	(2) $v_2 = 900$	(3) $900 > v_2 > b_1$	(4) $900 > v_2 = b_1 > 0$	(5) $v_2 = b_1 = 0$	(6) $v_2 < b_1$
$900 = b_1 > b_3 > 0$	900	$[0, 900]$				$[0, b_1)$
$900 > b_1 > b_3 > 0$	$(b_1, 900]$	$(b_1, 900]$	$(b_1, 900]$	$[0, 900]$		$[0, b_1)$
$900 = b_1 > b_3 = 0$	900	$[0, 900]$				$[0, b_1)$
$900 > b_1 > b_3 = 0$	$(b_1, 900]$	$(b_1, 900]$	$(b_1, 900]$	$[0, 900]$		$[0, b_1)$
$900 = b_1 = b_3$	900	$[0, 900]$				$[0, b_1)$
$900 > b_1 = b_3 > 0$	$(b_1, 900]$	$(b_1, 900]$	$(b_1, 900]$	$[0, 900]$		$[0, b_1)$
$b_1 = b_3 = 0$	$(0, 900]$	$(0, 900]$	$(0, 900]$		$[0, 900]$	

In column (1) of Table S16, firm 2 prefers not to sell TV station 2 at the opening price of 900. Firm 2 therefore either causes the reverse auction to fail at the outset if $b_1 = 900$ or withdraws first if $b_1 < 900$. In column (2), firm 2 is indifferent between selling TV station 2 at the opening price of 900 and not selling it. Firm 2 therefore bids anything if $b_1 = 900$ or withdraws first if $b_1 < 900$. In column (3), firm 2 prefers not to sell TV station 2 at a price of b_1. Firm 2 therefore withdraws first. In column (4) and (5), firm 2 is indifferent between selling TV station 2 at a price of b_1 and not selling it. Firm 2 therefore bids anything. In column (6), firm 2 prefers to sell TV station 2 at a price of b_1. Firm 2 therefore does not withdraw first. $\square$

Using Proposition 5, the expected profit of firm 1 if it bids $b_1 \in [0, 900]$ and $b_3 \in [0, 900]$ can be written as

$$
\begin{aligned}
E\pi_1(b_1, b_3; v_1, v_3, \sigma) \quad = \quad & \int_{900}^{\infty} (2 \cdot 900 - v_1 - v_3)\, 1\,(900 > \max\{b_1, b_3\})\, d\Phi_2(\tilde{v}_2) \\
& + \int_{0}^{900} (b_1 - v_3)\, 1\,(b_1 > \max\{\tilde{v}_2, b_3\}) \\
& + (2\tilde{v}_2 - v_1 - v_3)\, 1\,(\tilde{v}_2 > \max\{b_1, b_3\}) \\
& + (b_3 - v_1)\, 1\,(b_3 > \max\{b_1, \tilde{v}_2\}) \\
& + \left(\frac{1}{2}(b_3 - v_1) + \frac{1}{2}(b_1 - v_3)\right) 1\,(900 > b_1 = b_3 > \tilde{v}_2)\, d\Phi_2(\tilde{v}_2) \\
& + \int_{-\infty}^{0} (b_1 - v_3)\, 1\,(b_1 > b_3) \\
& + (b_3 - v_1)\, 1\,(b_3 > b_1) \\
& + \left(\frac{1}{2}(b_3 - v_1) + \frac{1}{2}(b_1 - v_3)\right) 1\,(900 > b_1 = b_3 > 0) \\
& - (v_1 + v_3)\, 1\,(b_1 = b_3 = 0)\, d\Phi_2(\tilde{v}_2).
\end{aligned}
\tag{S4}
$$

We assume $v_1 = 100$ and $v_3 = 300$ as in Section 3.1. Towards determining $b_1(100, 300, \sigma)$ and $b_3(100, 300, \sigma)$, the following propositions show that firm 1 always bids $b_1 < b_3$.

Proposition 6. *$E\pi_1(0, 0; 100, 300, \sigma) < E\pi_1(0, \epsilon; 100, 300, \sigma)$ and $E\pi_1(b, b; 100, 300, \sigma) < E\pi_1(b - \epsilon, b; 100, 300, \sigma)$ for all $b \in (0, 900]$ for any sufficiently small $\epsilon > 0$.*

Hence, firm 1 never bids $b_1 = b_3$.

Proof. First, consider $b = 0$. Then plugging into equation (S4) yields

$$\begin{aligned}
E\pi_1(0,0;100,300,\sigma) &= \int_{900}^{\infty} (2\cdot 900 - 100 - 300)\, d\Phi_2(\tilde{v}_2) \\
&\quad + \int_{0}^{900} (2\tilde{v}_2 - 100 - 300)\, d\Phi_2(\tilde{v}_2) \\
&\quad - \int_{-\infty}^{0} (100 + 300)\, d\Phi_2(\tilde{v}_2) \\
&< \int_{900}^{\infty} (2\cdot 900 - 100 - 300)\, d\Phi_2(\tilde{v}_2) \\
&\quad + \int_{\epsilon}^{900} (2\tilde{v}_2 - 100 - 300)\, d\Phi_2(\tilde{v}_2) \\
&\quad + \int_{-\infty}^{\epsilon} (\epsilon - 100)\, d\Phi_2(\tilde{v}_2) \\
&= E\pi_1(0,\epsilon;100,300,\sigma)
\end{aligned}$$

for any sufficiently small $\epsilon > 0$. Consider next $b \in (0, 900)$. Then plugging into equation (S4) yields

$$\begin{aligned}
E\pi_1(b,b;100,300,\sigma) &= \int_{900}^{\infty} (2\cdot 900 - 100 - 300)\, d\Phi_2(\tilde{v}_2) \\
&\quad + \int_{b}^{900} (2\tilde{v}_2 - 100 - 300)\, d\Phi_2(\tilde{v}_2) \\
&\quad + \int_{-\infty}^{b} \left(b - \frac{1}{2}100 - \frac{1}{2}300\right) d\Phi_2(\tilde{v}_2) \\
&< \int_{900}^{\infty} (2\cdot 900 - 100 - 300)\, d\Phi_2(\tilde{v}_2) \\
&\quad + \int_{b}^{900} (2\tilde{v}_2 - 100 - 300)\, d\Phi_2(\tilde{v}_2) \\
&\quad + \int_{-\infty}^{b} (b - 100)\, d\Phi_2(\tilde{v}_2) \\
&= E\pi_1(b-\epsilon,b;100,300,\sigma).
\end{aligned}$$

Finally, consider $b = 900$. Then plugging into equation (S4) yields

$$\begin{aligned}
E\pi_1(900,900;100,300,\sigma) &= 0 \\
&< \int_{-\infty}^{900} (900 - 100) d\Phi_2(\tilde{v}_2) \\
&= E\pi_1(900-\epsilon,900;100,300,\sigma).
\end{aligned}$$

□

Proposition 7. $b_1 > b_3$ implies $E\pi_1(b_1, b_3; 100, 300, \sigma) > E\pi_1(b_3, b_1; 100, 300, \sigma)$.

Hence, firm 1 never bids $b_1 > b_3$. Taken together, Propositions 6 and 7 imply that firm 1 always bids $b_1 < b_3$.

Proof. Consider first $900 > b_1 > b_3 \geq 0$. Then plugging into equation (S4) yields

$$\begin{aligned} E\pi_1(b_1, b_3; 100, 300, \sigma) &= \int_{900}^{\infty} (2 \cdot 900 - 100 - 300)\, d\Phi_2(\tilde{v}_2) \\ &\quad + \int_{b_1}^{900} (2\tilde{v}_2 - 100 - 300)\, d\Phi_2(\tilde{v}_2) \\ &\quad + \int_{-\infty}^{b_1} (b_1 - 300)\, d\Phi_2(\tilde{v}_2) \\ &< \int_{900}^{\infty} (2 \cdot 900 - 100 - 300)\, d\Phi_2(\tilde{v}_2) \\ &\quad + \int_{b_1}^{900} (2\tilde{v}_2 - 100 - 300)\, d\Phi_2(\tilde{v}_2) \\ &\quad + \int_{-\infty}^{b_1} (b_1 - 100)\, d\Phi_2(\tilde{v}_2) \\ &= E\pi_1(b_3, b_1; 100, 300, \sigma). \end{aligned}$$

Next consider $900 = b_1 > b_3 \geq 0$. Then plugging into equation (S4) yields

$$\begin{aligned} E\pi_1(900, b_3; 100, 300, \sigma) &= \int_{-\infty}^{900} (900 - 300)\, d\Phi_2(\tilde{v}_2) \\ &< \int_{-\infty}^{900} (900 - 100)\, d\Phi_2(\tilde{v}_2) \\ &= E\pi_1(b_3, 900; 100, 300, \sigma). \end{aligned}$$

□

Using Propositions 6 and 7, the expected profit of 1 firm if $b_3 < 900$ becomes

$$\begin{aligned}
E\pi_1(b_1, b_3; 100, 300, \sigma) &= \int_{900}^{\infty} (2 \cdot 900 - 100 - 300)\, d\Phi_2(\tilde{v}_2) \\
&\quad + \int_{b_3}^{900} (2\tilde{v}_2 - 100 - 300)\, d\Phi_2(\tilde{v}_2) \\
&\quad + \int_{0}^{b_3} (b_3 - 100)\, d\Phi_2(\tilde{v}_2) \\
&\quad + \int_{-\infty}^{0} (b_3 - 100)\, d\Phi_2(\tilde{v}_2) \\
&= 1400 \left(1 - \Phi\left(\frac{900 - v_2}{\sigma}\right)\right) \\
&\quad + (2v_2 - 400) \left(\Phi\left(\frac{900 - v_2}{\sigma}\right) - \Phi\left(\frac{b_3 - v_2}{\sigma}\right)\right) \\
&\quad + 2\sigma \left(\phi\left(\frac{b_3 - v_2}{\sigma}\right) - \phi\left(\frac{900 - v_2}{\sigma}\right)\right) \\
&\quad + (b_3 - 100)\, \Phi\left(\frac{b_3 - v_2}{\sigma}\right) \qquad \text{(S5)}
\end{aligned}$$

and

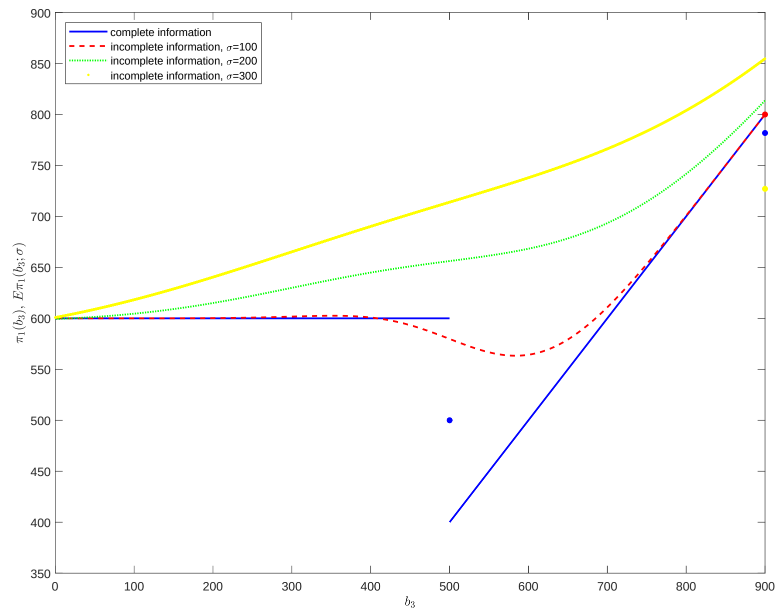
$$\begin{aligned}
E\pi_1(b_1, 900; 100, 300, \sigma) &= \int_{-\infty}^{900} (900 - 100)\, d\Phi_2(\tilde{v}_2) \\
&= 800\Phi\left(\frac{900 - v_2}{\sigma}\right)
\end{aligned}$$

if $b_3 = 900$. Note that the expected profit of firm 1 depends solely on b_3; hence, $b_1 \in [0, b_3)$ is indeterminate. Note also that $\lim_{b_3 \to 900-} E\pi_1(b_1, b_3; 100, 300, \sigma) > E\pi_1(b_1, 900; 100, 300, \sigma)$; hence, firm 1 never bids $b_3 = 900$.

To explore the relationship between the game of incomplete information as $\sigma \to 0^+$ so that beliefs collapse at the true reservation values and the game of complete information, we first assume $v_2 = 500$ as in Section 3.1. The expected profit of firm 1 in the game of incomplete information becomes

$$\begin{aligned}
&E\pi_1(b_1, b_3; 100, 300, \sigma) \\
&= \begin{cases} 1400 - 800\Phi\left(\frac{400}{\sigma}\right) + (b_3 - 700)\, \Phi\left(\frac{b_3 - 500}{\sigma}\right) + 2\sigma\left(\phi\left(\frac{b_3 - 500}{\sigma}\right) - \phi\left(\frac{400}{\sigma}\right)\right) & \text{if} \quad b_3 < 900, \\ 800\Phi\left(\frac{400}{\sigma}\right) & \text{if} \quad b_3 = 900. \end{cases} \qquad \text{(S6)}
\end{aligned}$$

Figure S3: Expected profit and profit of firm 1 in equations (S6) and (S7) with $v_2 = 500$



For comparison, in the game of complete information the profit of firm 1 in equation (S1) becomes

$$\pi_1(b_1, 500, b_3) = \begin{cases} 600 & \text{if} \quad b_3 < 500, \\ b_3 - 100 & \text{if} \quad b_3 > 500, \\ 500 & \text{if} \quad b_3 = 500, \end{cases} \tag{S7}$$

where we assume that firm 2 truthfully bids $b_2 = 500$ and firm 1 bids $b_1 < b_3$ as in the game of incomplete information. Note that in the game of complete information the profit of firm 1 again depends solely on b_3 and that firm 1 always bids such that $b_3 = 900$.

Figure S3 plots the expected profit of firm 1 in equation (S6) for various values of σ and the profit of firm 1 in equation (S7). As $\sigma \to 0^+$, the expected profit of firm 1 under incomplete information closely resembles the profit of firm 1 under complete information. Moreover, for a wide range of values of σ, $b_3(100, 300, \sigma)$ in the game of incomplete information is arbitrarily close to (but different from) $b_3 = 900$ in the game of complete information. Close to extreme overbidding thus arises in the game of incomplete information.

To further explore the relationship between the games of complete and incomplete information, in Online Appendix A.1, we consider a variant the example in Section 3.1 in which we replace the reservation value of TV station 2 by $v_2 = 700$. The expected profit of firm 1 in the game of incomplete information becomes

$$
\begin{aligned}
&E\pi_1(b_1, b_3; 100, 300, \sigma) \\
&= \begin{cases} 1400 - 400\Phi\left(\frac{200}{\sigma}\right) + (b_3 - 1100)\,\Phi\left(\frac{b_3 - 700}{\sigma}\right) + 2\sigma\left(\phi\left(\frac{b_3-700}{\sigma}\right) - \phi\left(\frac{200}{\sigma}\right)\right) & \text{if} \quad b_3 < 900, \\ 800\Phi\left(\frac{200}{\sigma}\right) & \text{if} \quad b_3 = 900. \end{cases}
\end{aligned} \tag{S8}
$$

For comparison, in the game of complete information the profit of firm 1 in equation (S3) becomes

$$
\pi_1(b_1, 700, b_3) = \begin{cases} 1000 & \text{if} \quad b_3 < 700, \\ b_3 - 100 & \text{if} \quad b_3 > 700, \\ 800 & \text{if} \quad b_3 = 700, \end{cases} \tag{S9}
$$

where we assume that firm 2 truthfully bids $b_2 = 700$ and firm 1 bids $b_1 < b_3$ as in the game of incomplete information. Note that in the game of complete information the profit of firm 1 again depends solely on b_3 and that firm 1 always bids $b_3 \in [0, 700)$.

Figure S4 is analogous to Figure S3. As $\sigma \to 0^+$, the expected profit of firm 1 under incomplete information again closely resembles the profit of firm 1 under complete information. Figure S4 further shows that $b_3(100, 300, \sigma)$ in the game of incomplete information gets close to the reservation value $v_3 = 300$ of TV station 3 as $\sigma \to 0+$. In this example, a small amount of incomplete information thus appears to single out truthful bidding. Finally, Figure S4 shows that $b_3(100, 300, \sigma)$ gets close to 900 as $\sigma \to \infty$. A large amount of incomplete information thus appears to support close to extreme overbidding even though firm 1 never bids $b_3 = 900$ in the game of complete information as we show in Online Appendix A.1.

B Data sources

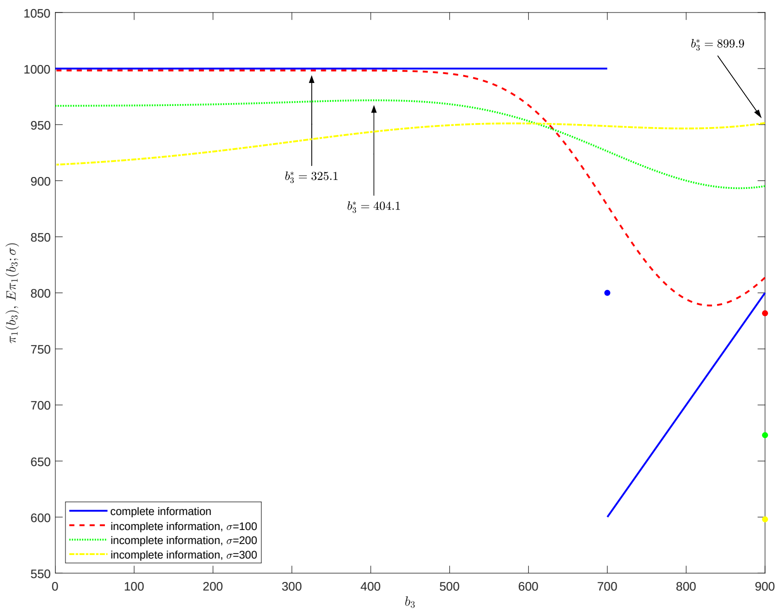
In this appendix, we discuss several details of the data sources we rely on and describe how we construct our sample and primary variables.

B.1 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 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

Figure S4: Expected profit and profit of firm 1 in equations (S8) and (S9) with $v_2 = 700$



2015.[S4] Transaction histories are provided from 2003 to 2013.

For commercial full-power and low-power class-A stations, advertising revenue is missing for 4,892, or 24.9%, station-year observations. Table S17 shows the share of station-year observations with missing advertising revenue for commercial stations. As the top panel shows, advertising revenue is missing for almost all satellite stations because BIA subsumes their advertising revenues into those of their parent primary stations.[S5] Missing values are further concentrated among low-power class-A stations. Given this prevalence, we supplement the sample with data on 1,331 LPTV stations with non-missing revenue data. LPTV stations are not auction-eligible, but are more comparable to low-power class-A stations than full-power stations. Focusing only on full-power and low-power class-A stations, the bottom panel of Table S17 summarizes the prevalence of missing revenue data by affiliation. 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 for commercial full-power and low-power class-A stations

[S4] 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.

[S5] 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 to 78 primary stations because BIA does not provide this information.

Table S17: Missing advertising revenue for commercial stations

	Station-year obs.	Missing advertising revenue	
		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

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 LPTV stations, an indicator for full-power stations, fixed effects for the eleven network affiliations in Table S17, fixed effects for the interaction of affiliation groups ((1) ABC, CBS, NBC, and Fox; (2) CW, My Network TV, United Paramount, Warner Bros, and Spanish-language networks; (3) Independents and other minor networks) 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 A.1), and the log of DMA population (in thousand). We report the parameter estimates in Table S18. 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.

With the parameter estimates in hand, we impute advertising revenue AD_{jt} for primary stations, where missing, as $\widehat{AD}_{jt} = e^{\widehat{\ln AD}_{jt} + \frac{\hat{\sigma}^2}{2}}$ 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

Table S18: Advertising revenue imputation by year

	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2015
$\ln(InterferenceFreePop_{jt})$	0.481***	0.470***	0.406***	0.365***	0.333***	0.294***	0.304***	0.302***	0.307***	0.264***	0.268***	0.225***
	(0.048)	(0.047)	(0.044)	(0.043)	(0.042)	(0.040)	(0.040)	(0.038)	(0.038)	(0.035)	(0.035)	(0.038)
Multicast	0.214***	0.195***	0.203***	0.134**	0.150***	0.146***	0.150***	0.090*	0.112**	0.081	0.075	0.143**
	(0.052)	(0.049)	(0.051)	(0.053)	(0.053)	(0.052)	(0.052)	(0.051)	(0.052)	(0.050)	(0.050)	(0.061)
LPTV	-0.020	-0.277**	-0.241*	-0.304**	-0.310**	-0.316***	-0.268**	-0.120	-0.182	-0.132	-0.157	-0.164
	(0.146)	(0.138)	(0.134)	(0.130)	(0.121)	(0.116)	(0.114)	(0.108)	(0.110)	(0.105)	(0.104)	(0.105)
Full-power	0.735***	0.620***	0.753***	0.846***	0.864***	0.860***	0.888***	0.969***	0.909***	0.969***	0.952***	1.022***
	(0.115)	(0.114)	(0.110)	(0.111)	(0.104)	(0.100)	(0.101)	(0.095)	(0.096)	(0.093)	(0.092)	(0.094)
Owns >1 station in DMA	0.029	0.019	0.056	0.070	0.092*	0.106**	0.109**	0.081	0.107**	0.102**	0.116**	0.124**
	(0.056)	(0.055)	(0.055)	(0.054)	(0.054)	(0.052)	(0.052)	(0.051)	(0.052)	(0.050)	(0.050)	(0.052)
Owns 2-10 stations across DMAs	0.108	0.093	0.087	0.047	0.082	-0.005	0.111	0.090	0.180**	0.173**	0.165**	0.195**
	(0.080)	(0.079)	(0.082)	(0.084)	(0.084)	(0.081)	(0.085)	(0.083)	(0.083)	(0.083)	(0.084)	(0.093)
Owns >10 stations across DMAs	0.342***	0.304***	0.251***	0.247***	0.208**	0.181**	0.225***	0.240***	0.353***	0.277***	0.275***	0.342***
	(0.079)	(0.078)	(0.081)	(0.085)	(0.085)	(0.081)	(0.084)	(0.082)	(0.082)	(0.082)	(0.081)	(0.087)
# Stations in DMA	0.002	0.005	0.006	0.005	0.003	0.002	0.007	0.011**	0.012**	0.019***	0.010	0.005
	(0.005)	(0.005)	(0.005)	(0.005)	(0.005)	(0.005)	(0.006)	(0.006)	(0.006)	(0.006)	(0.007)	(0.005)
# Major network affiliates in DMA	-0.046	-0.032	-0.018	0.003	-0.003	-0.003	0.030	0.064	0.076*	0.146***	0.074	-0.004
	(0.032)	(0.032)	(0.032)	(0.033)	(0.033)	(0.034)	(0.038)	(0.040)	(0.041)	(0.045)	(0.047)	(0.034)
$WealthIndex_{jt}$	0.125***	0.120***	0.133***	0.123***	0.123***	0.133***	0.133***	0.148***	0.150***	0.157***	0.147***	0.149***
	(0.024)	(0.023)	(0.024)	(0.024)	(0.024)	(0.023)	(0.024)	(0.023)	(0.023)	(0.022)	(0.023)	(0.025)
$CompIndex_{jt}$	0.026	-0.017	-0.053	-0.092	-0.060	-0.048	-0.152	-0.252**	-0.275**	-0.462***	-0.245*	-0.075
	(0.081)	(0.084)	(0.088)	(0.091)	(0.090)	(0.093)	(0.105)	(0.115)	(0.121)	(0.130)	(0.134)	(0.086)
$\ln(DMAPop_{jt})$	0.361***	0.385***	0.409***	0.469***	0.502***	0.507***	0.500***	0.509***	0.493***	0.529***	0.528***	0.507***
	(0.053)	(0.052)	(0.051)	(0.051)	(0.049)	(0.048)	(0.047)	(0.045)	(0.045)	(0.043)	(0.043)	(0.046)
Network affiliation fixed effects	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Affiliation groups × U.S. states	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Adjusted R^2	0.994	0.994	0.993	0.993	0.992	0.993	0.992	0.993	0.992	0.992	0.992	0.991
N	1191	1215	1247	1307	1343	1364	1371	1379	1397	1415	1421	1454

between the primary station and any affiliated satellite stations in proportion to their interference free population.

B.2 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 S19 shows the resulting 66 tables in 2012.[S6] The number of tables fluctuates slightly year-by-year because NAB imposes a minimum of ten TV stations per aggregation category to ensure confidentiality.[S7,S8] Note that a TV station may feature in more than one table. For example, WABC-TV, 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 S20.

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.

[S6] We exclude 15 aggregation categories that are defined by total revenue because the BIA data is restricted to advertising revenue.

[S7] In 2012, NAB received 785 responses to 1,288 questionnaires, a response rate of 60.9%.

[S8] 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 Appendix A.1.

Table S19: 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 S20: Sample NAB data for select aggregation categories in 2012

	Advertising revenue ($ million)	Cash flow ($ million)				Non-broadcast 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

C Private equity firms

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.

C.1 Timeline of acquisitions and sales

Figures S5-S7 document the timeline of acquisitions (black) and sales (red) of TV stations by LocusPoint, NRJ, and OTA. As stated in the main text, from 2010 to 2015 these private equity firms acquired 48 UHF stations. In addition, LocusPoint acquired W33BY-D, WMJF-CD, and WBNF-CD for $4.8 million and sold them to HME Equity Fund II LLC for $23.75 million before the reverse auction;[S9] we exclude these UHF stations from Figure S5. NRJ acquired KFWD for $9.9 million;[S10] we include this VHF station in Figure S6. Finally, LocusPoint acquired WPHA-CD from D.T.V. LLC in a deal that apparently has not been consummated due to a law suit between the two parties; we exclude this UHF station from Figure S5.[S11]

We obtain the holdings of LocusPoint, NRJ, and OTA as of 2015 from BIA. We rely on news coverage to confirm these holdings and identify any changes to them.[S12] We have been unable to ascertain the purchase price for W24BB-D and thus set it to zero. If multiple TV stations were

[S9] See http://www.tvnewscheck.com/article/92491/hme-equity-closes-on-purchase-of-3-lptvs, accessed on March 17, 2018.

[S10] See http://www.tvnewscheck.com/article/89486/nrj-tv-buys-dallas-vhf-for-99-million, accessed on April 30, 2018.

[S11] See https://publicfiles.fcc.gov/api/service/tv/application/1709537.html and Paragraph 81 of https://transition.fcc.gov/eb/Orders/2016/FCC-16-41A1.html, accessed on April 1, 2018.

[S12] We primarily track TV station trading news through http://www.tvnewscheck.com/ and https://www.rbr.com/.

Table S21: 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	

acquired in a single transaction, then we allocate the total purchase price to each acquired TV station in proportion to its interference free population.

The FCC released the identity of the TV stations that relinquished their licenses in the reverse auction along with their payouts. OTA voluntarily surrendered the license of WJPW-CD to the FCC.[S13] We exclude from Table 2 and Figures S5-S7 any sales of non-spectrum assets such as programming contracts, or equipment.[S14] We set the sales price of non-spectrum assets to zero if we cannot ascertain it separately in a transaction involving multiple TV stations.

C.2 Comparison of TV stations acquired by private equity firms and other transactions

Table S21 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, the 48 TV stations acquired by the three private equity firms have higher broadcast volume, due to both higher interference free population and higher interference count.

[S13]See https://enterpriseefiling.fcc.gov/dataentry/public/tv/draftCopy.html?displayType=html&appKey=25076ff35f490dae015f4fa9968c0e0d&id=25076ff35f490dae015f4fa9968c0e0d&goBack=N, accessed on April 30, 2018.

[S14]NRJ sold the non-spectrum assets of WGCB-TV, WMFP, and WTVE after relinquishing their licenses in the reverse auction and OTA sold the non-spectrum assets of KTLN-TV, WEBR-CD, WYCN-CD, and WLWC, see http://www.tvnewscheck.com/article/108526/station-trading-roundup-5-deals-259m, accessed on April 1, 2018, https://tvnewscheck.com/article/242153/station-trading-roundup-1-deal-81-2m/, accessed on July 14, 2020, https://tvnewscheck.com/article/108888/station-trading-roundup-1-deal-12500/, accessed on July 14, 2020, https://tvnewscheck.com/article/108526/station-trading-roundup-5-deals-25-9m/, accessed on July 14, 2020, and https://tvnewscheck.com/article/106271/nexstar-buys-zombie-station-wlwc-for-4-1m/, accessed on July 14, 2020.

Figure S5: Timeline of LocusPoint's acquisitions (black) and sales (red) of TV stations

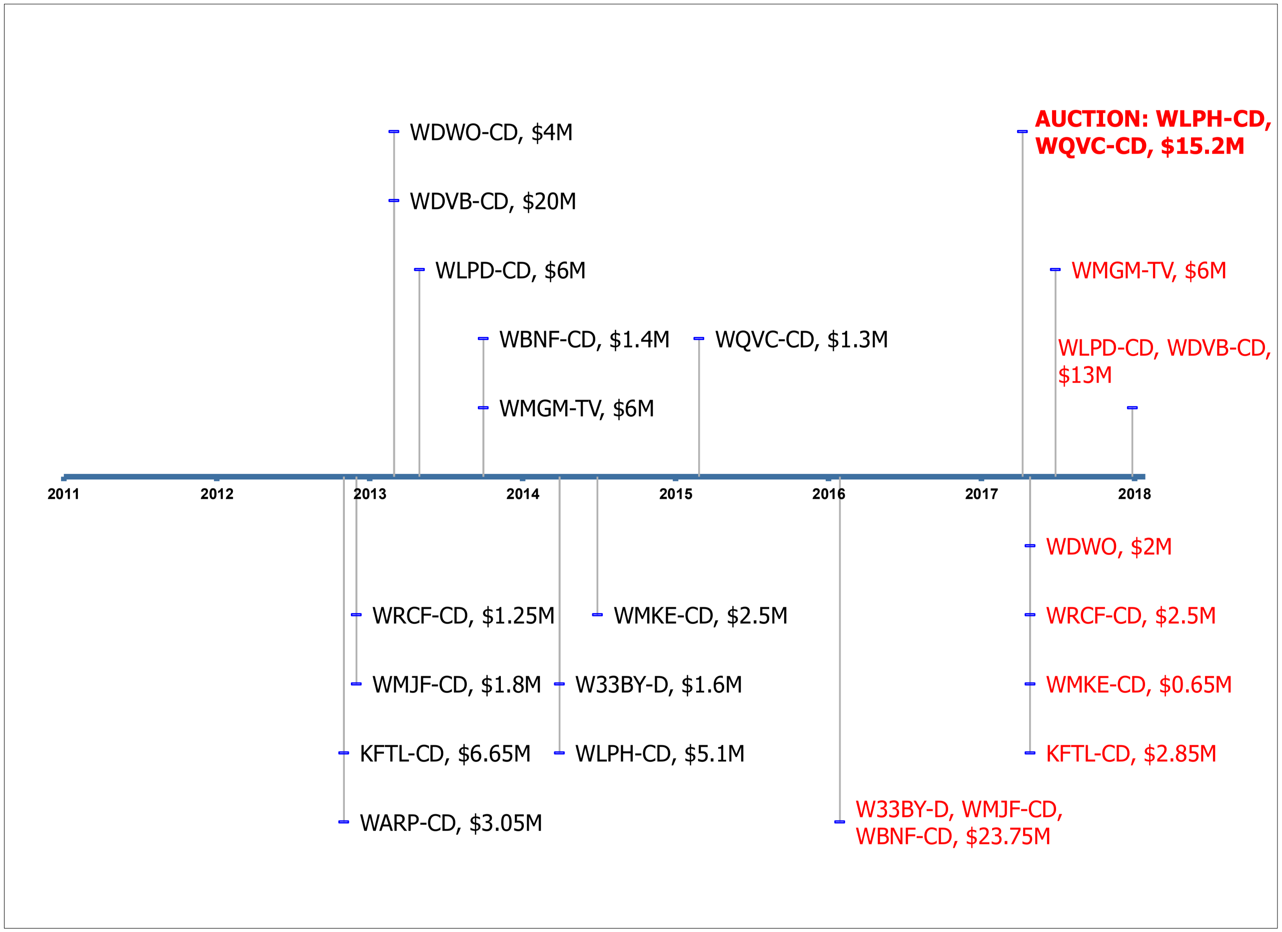


Figure S6: Timeline of NRJ's acquisitions (black) and sales (red) of TV stations

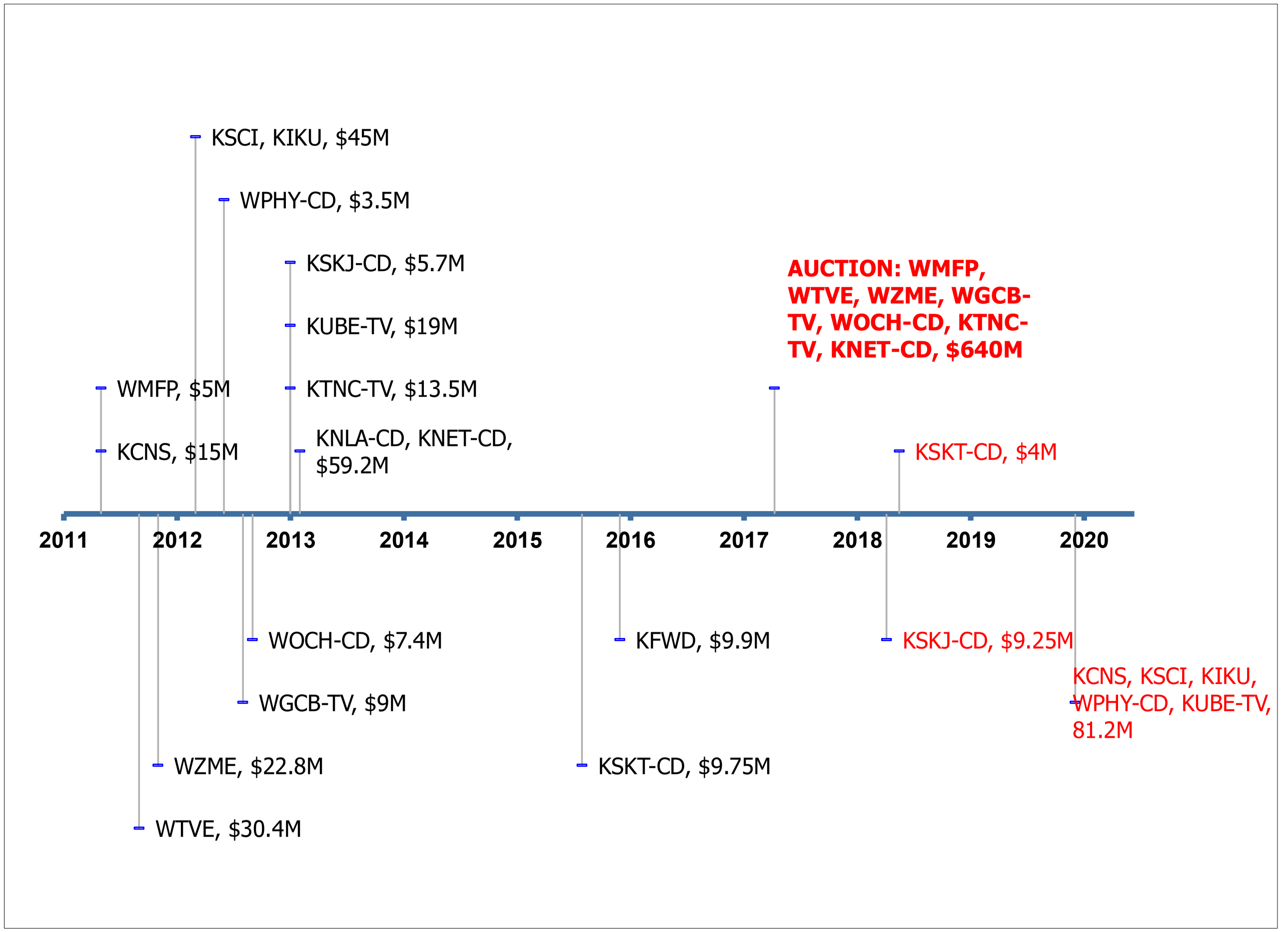


Figure S7: Timeline of OTA's acquisitions (black) and sales (red) of TV stations

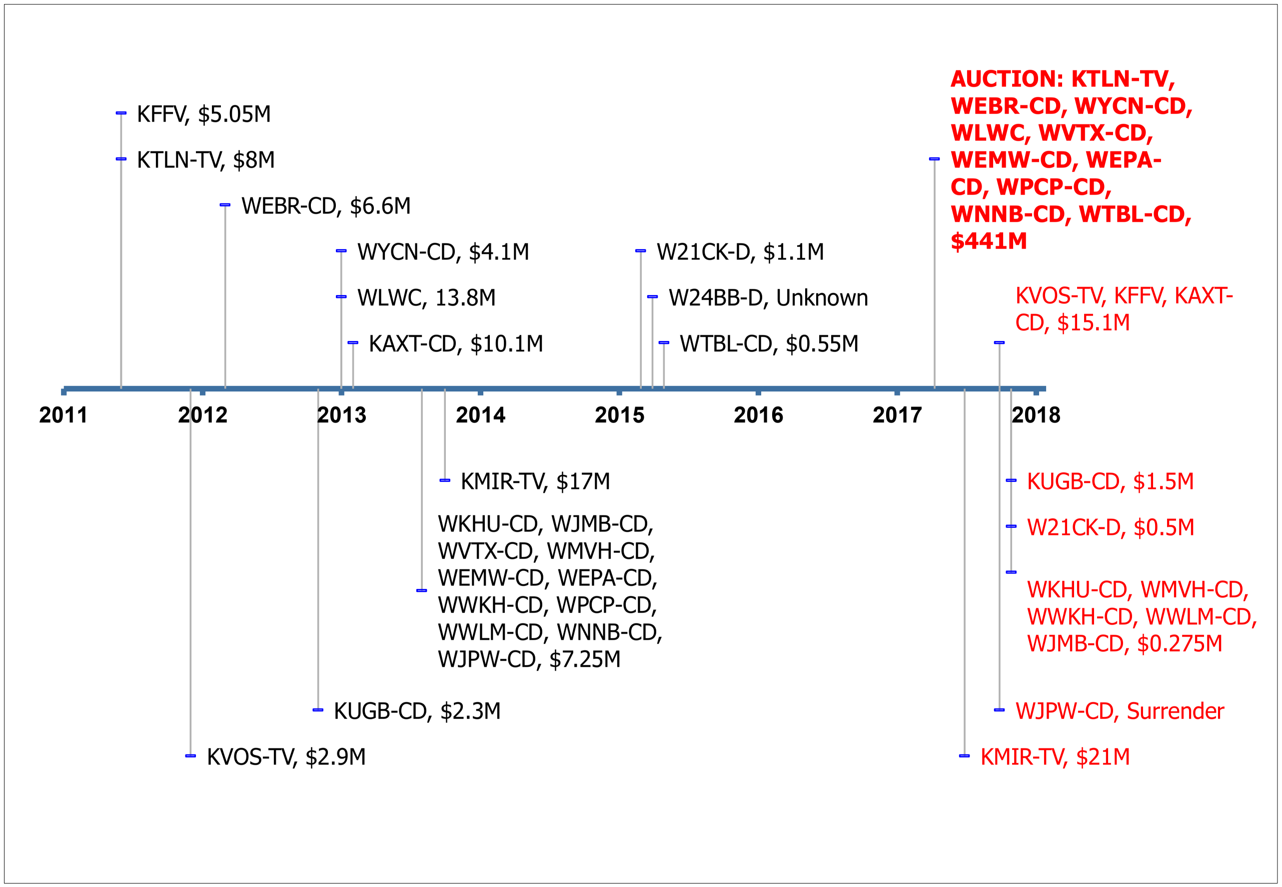


Table S22: Repacking regions for all 202 DMAs

	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	18.8	1	6.9	13.6	21.6	160.0
Area (square miles)	18.1	1	7.8	14.0	21.4	170.3

D Regions

We obtain a crosswalk between DMAs and zip codes from Sood (2018) and zip code area from the Missouri Census Data Center, MABLE/Geocorr14: Geographic Correspondence Engine.[S15] Table S22 covers all 202 DMAs.

E Reservation values

In this appendix, we provide further details on predicted values and goodness of fit.

E.1 Cash flows

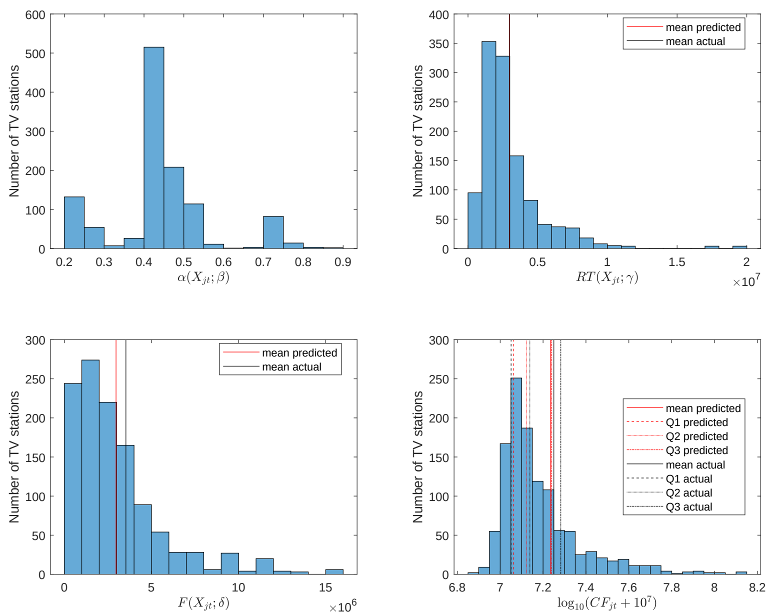
The parameter estimates $\hat{\theta}$ in Table A1 in Appendix A.1 indicate that Warner Bros and Spanish language networks affiliates retain the highest share of advertising revenues. Except for Fox affiliates, major network affiliates retain a higher share of advertising revenue than minor networks; however, the retained share of Fox affiliates rises over time. TV stations that are part of a joint sales or local marketing agreement retain a higher share of advertising revenue. The retained share falls over time, bottoming out in 2009 before bouncing back in recent years.

Figure S8 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 0.21 and 0.86 across TV stations, with an average of 0.44. We predict non-broadcast revenue to be between \$0.21 million and \$19.39 million, averaging \$2.98 million, and we predict fixed cost to be between \$0.00 million and \$15.78 million, averaging \$2.97 million. Finally, we predict cash flow to be between \$-2.58 million and \$129.77 million across TV stations, with an average of \$7.21 million.

The cash flow model fits the data well. In Figure S8, we overlay predicted moments as red lines and actual moments as reported in the NAB data (table "All Stations, All Markets") as black lines. NAB reports an average non-broadcast revenue of \$2.98 million in line with our prediction of \$2.98 million (upper right panel). We somewhat underestimate fixed cost, where NAB reports

[S15] See http://mcdc.missouri.edu/websas/geocorr14.html, accessed on July 22, 2018.

Figure S8: 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.

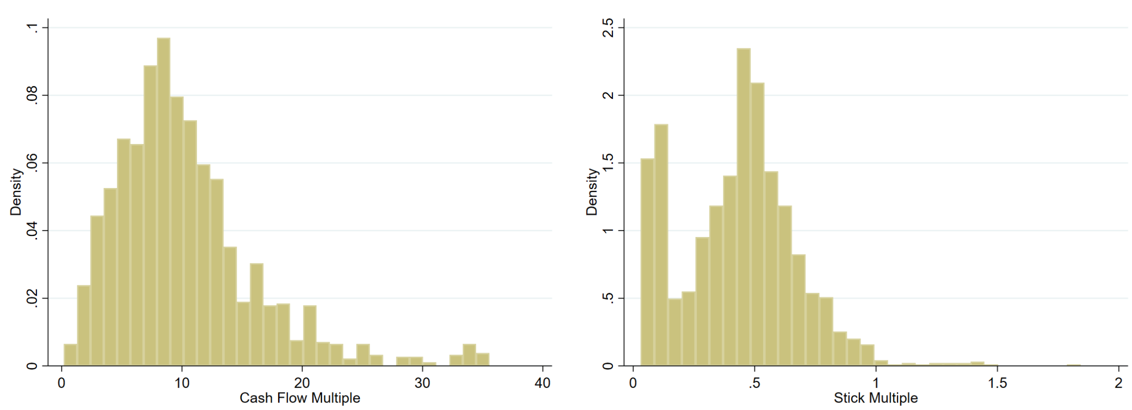
an average of \$3.53 million compared to our prediction of \$2.97 million (lower left panel). Turning to cash flow (lower right panel), NAB reports an average of \$7.80 million and first, second, and third quartiles of \$1.24 million, \$3.75 million, and \$9.18 million. This compares to our predictions of \$7.21 million, \$1.51 million, \$3.29 million, and \$7.38 million, respectively.

To further assess the fit of the cash flow model, Table S23 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 0.83 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.

E.2 Multiples

With the estimates for equations (A1) and (A2) in hand, we set $\epsilon_{jt}^{CF} = \epsilon_{jt}^{Stick} = 0$ and predict the cash flow and stick multiples for the 1,670 auction-eligible UHF stations that are located outside Puerto Rico and the Virgin Islands. Figure S9 illustrates the distributions of the predicted cash flow multiple (left panel) and stick multiple (right panel).

Figure S9: Distributions of predicted cash flow and stick multiples



F Pseudo code for algorithm

There are N TV stations in the focal DMA and its neighbors. Throughout we fix the vector $b = (b_1, \ldots, b_N)$ of their bids. Using the notation in Section 3, PO_j is the payout of TV station j

Table S23: Cash flow, non-broadcast revenue, and fixed cost moments and fit measures

	Number of moments	Correlation	Mean abs. deviation		Mean deviation	
			$ 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

Algorithm 1 Full repacking

Initialization: Set $\tau = 1$, $P = 900$, $A = \{1, \ldots, N\}$, $I = \emptyset$, and $F = \emptyset$.
Repeat

1. Let $Y = \{k \in A | b_k \geq P\}$ be the set of active TV stations that opt to remain on the air at a base clock price of P. Set $A \leftarrow A \setminus Y$, $I \leftarrow I \cup Y$, and $PO_j = \pi_j = 0$ for all $j \in Y$.
2. If $\tau = 1$ and $S(Y, R) \neq 1$, then these TV stations cannot be repacked and the reverse auction has failed at the outset (see footnote 26). Set a flag, $PO_j = \pi_j = 0$ for all $j \in A$, and terminate.
3. For all $k \in A$ do
   (a) If $S(I \cup \{k\}, R) \neq 1$, then active TV station k cannot additionally be repacked. In this case, set $A \leftarrow A \setminus \{k\}$, $F \leftarrow F \cup \{k\}$, $PO_k = \varphi_k P$, and $\pi_k = \varphi_k P - v_k$.
4. End
5. If $A \neq \emptyset$, then set $P = \max_{j \in A} b_j$, $\tau \leftarrow \tau + 1$, and continue with the decreased based clock price.
6. If $P = 0$, then the reverse auction concludes with a base clock price of 0 (see footnote 25). Set a flag, $F \leftarrow F \cup A$, $PO_j = 0$ and $\pi_j = -v_j$ for all $j \in A$, and $A = \emptyset$ (in this order).

Until $A = \emptyset$.

from the reverse auction and π_j its profit. The base clock price is P, the set of active TV stations is A, the set of inactive TV stations is I, and the set of frozen TV stations is F, where we omit the dependence of these objects on the round τ of the reverse auction.

Full repacking. Algorithm 1 describes the algorithm that we use under full repacking as well as under naive bidding with $b = (s_1, \ldots, s_N)$. On line 1, $|Y| \leq 1$ by assumption, except possibly if $\tau = 1$, so that at most one active TV station opts to remain on the air.

Limited repacking. Algorithm 2 describes the algorithm that we use under limited repacking. It takes the output of the algorithm under full repacking and naive bidding as an input.

We relabel TV stations such that TV stations $\{1, \ldots, K\}$ are in the focal DMA and TV stations $\{K+1, \ldots, N\}$ are in the neighboring DMAs. We denote by $F^{*,full,naive}$ the (appropriately relabeled) set of frozen TV stations at the conclusion of the reverse auction from the algorithm under full repacking and naive bidding. In the initialization, $F^{*,full,naive} \cap \{K+1, \ldots, N\}$ is the set of TV stations in neighboring DMAs that have been frozen under full repacking and naive bidding; these TV stations cannot freeze another TV stations under limited repacking. On line 3, $A \cap \{1, \ldots, K\}$ is the set of active TV stations in the focal DMA; these are the only TV stations that can be frozen under limited repacking.

Algorithm 2 Limited repacking

Initialization: Set $\tau = 1$, $P = 900$, $A = \{1, \ldots, N\} \setminus \left(F^{*,full,naive} \cap \{K+1, \ldots, N\}\right)$, $I = \emptyset$, and $F = F^{*,full,naive} \cap \{K+1, \ldots, N\}$.

Repeat

1. Let $Y = \{k \in A | b_k \geq P\}$ be the set of active TV stations that opt to remain on the air at a base clock price of P. Set $A \leftarrow A \setminus Y$, $I \leftarrow I \cup Y$, and $PO_j = \pi_j = 0$ for all $j \in Y$.
2. If $\tau = 1$ and $S(Y, R) \neq 1$, then these TV stations cannot be repacked and the reverse auction has failed at the outset (see footnote 26). Set a flag, $PO_j = \pi_j = 0$ for all $j \in A$, and terminate.
3. For all $k \in A \cap \{1, \ldots, K\}$ do
   (a) If $S(I \cup \{k\}, R) \neq 1$, then active TV station k cannot additionally be repacked. In this case, set $A \leftarrow A \setminus \{k\}$, $F \leftarrow F \cup \{k\}$, $PO_k = \varphi_k P$, and $\pi_k = \varphi_k P - v_k$.
4. End
5. If $A \neq \emptyset$, then set $P = \max_{j \in A} b_j$, $\tau \leftarrow \tau + 1$, and continue with the decreased base clock price.
6. If $P = 0$, then the reverse auction concludes with a base clock price of 0 (see footnote 25). Set a flag, $F \leftarrow F \cup A$, $PO_j = 0$ and $\pi_j = -v_j$ for all $j \in A$, and $A = \emptyset$ (in this order).

Until $A = \emptyset$.

G Robustness

In this appendix, we explore the impact of limited repacking and underbidding on our results.

G.1 Limited repacking

We assess the effect of the limited repacking in two ways. 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 S24 shows that moving to full repacking reduces nationwide 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 S24 shows. A lowering of the clearing target, and the smaller number of TV stations that have 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.

Table S24: 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	2.478	182.609
	(0.360)	(8.942)
Full repacking	2.441	160.580
	(0.356)	(4.985)

Second, we compare limited to full repacking for the New York, NY, DMA under strategic bidding, as doing so for all 202 DMAs is not computationally feasible. As Table S25 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.

G.2 Underbidding

We investigate the impact of underbidding on payouts for the New York, NY, DMA under the 84 MHz clearing target and assume that the strategy space of TV station j is $b_j \in \{0, s_j, 900\}$ instead of $b_j \in \{s_j, 900\}$ if it is jointly owned. This increases the number strategy profiles from 189 to 8,575. To lighten the computational burden, we reduce to number of simulation draws from $N^S = 100$ to $N^S = 50$.

As Table S26 shows, allowing for underbidding has a small impact on payouts. Although allowing for underbidding enlarges the set of payout-unique equilibria, the overlap with the set of payout-unique equilibria in the base case that rules out underbidding is large. In the base case, we find 2,592 equilibria across simulation draws that map into 138 payout-unique equilibria. With underbidding, across the same draws, we find 13,234 equilibria that map into 200 payout-unique equilibria. Yet, 120 payout-unique equilibria appear in both the base case and with underbidding.

H Multi-market strategies

We continue with the Philadelphia, PA, DMA as a case study to illustrate how multi-market strategies may work. The 24 TV stations in the Philadelphia, PA, DMA are held by 18 owners. Twelve 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

Table S25: Payouts to TV stations in New York, NY, DMA under strategic bidding and full repacking

Payouts ($ billion)	Naive bidding	Strategic bidding Mean	Min	Median	Max	Payout increase at mean (%)
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)	

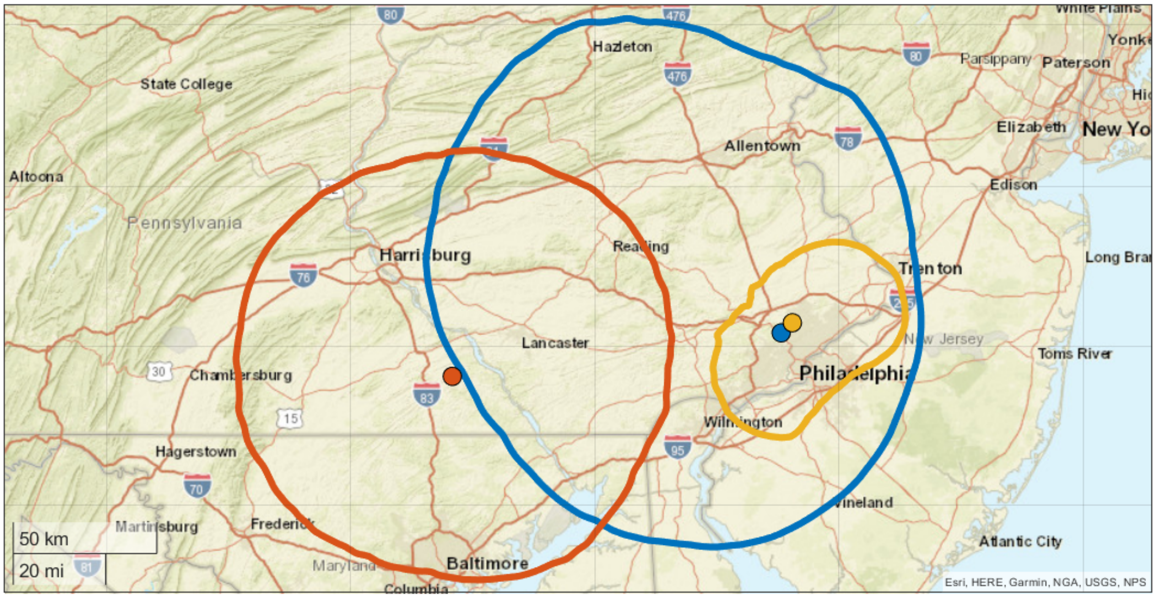
Notes: Payout increase at mean calculated as percent difference between mean payouts under strategic and naive bidding.

Table S26: Payouts to TV stations in New York, NY, DMA with underbidding

Payouts ($ billion)	Naive bidding	Strategic bidding Mean	Min	Median	Max	Payout increase at mean (%)
Panel A: 84 MHz clearing target						
Base case	0.375	0.410	0.398	0.409	0.423	9.5
	(0.103)	(0.109)	(0.109)	(0.108)	(0.112)	
With underbidding	0.375	0.411	0.395	0.411	0.425	9.6
	(0.103)	(0.112)	(0.113)	(0.112)	(0.112)	

Notes: Payout increase at mean calculated as percent difference between mean payouts under strategic and naive bidding. Using $N^S = 50$ simulation draws.

Figure S10: 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.

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 twelve 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 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 in the Philadelphia, PA, DMA in late 2011 and early 2012 for $30.4 million and $3.5 million, respectively. Figure S10 shows the overlap between the service contours of WGCB-TV (in red), WTVE (in blue), and WPHY-CD (in yellow).[S16] 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 S27 compares payouts to TV stations in the Philadelphia, PA, DMA under the multi-market strategy to payouts in our base case. On average across payout-unique equilibria and simulation draws, payouts increase by 4.8% under the 126 MHz clearing target and by 6.3% under the 84 MHz clearing target. The gains from strategic bidding increase as well

[S16]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.

Table S27: 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.

under the multi-market strategy. 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.

I Efficiency

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 below. 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.[S17]

Binary programming problem. There are N TV stations in the focal DMA and its neighbors with reservation values $(v_1, \ldots, v_N)$ in a given simulation draw. The clearing target defines the

[S17]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.

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

$$\max_x \sum_j \sum_c x_{j,c} v_j \tag{S10}$$

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.

Results. Table S28 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 of payouts in the actual reverse auction.[S18] 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.

[S18] To give a sense of the computational burden, the analysis took a total of roughly 13,000 CPU-days.

Table S28: Value loss ratio for top ten DMAs

		Clearing target	
	Payout rank	84 MHz	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.