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Ownership Concentration and Strategic Supply Reduction†

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We explore the implications of ownership concentration for the recently concluded incentive auction that repurposed spectrum from broadcast TV to mobile broadband usage in the United States. We document significant multilicense ownership of TV stations. We show that in the reverse auction, in which TV stations bid to relinquish their licenses, multilicense 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 percent and 42.4 percent. (D44, D47, H82, L13, L82, L88)

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 repurposed for mobile broadband usage. The ensuing incentive auction is the most novel auction designed since the inception of spectrum auctions in the United States 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 repurposed 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 US Treasury. In light of the social value of the

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repurposed 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.

Repurposing 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, 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 naïve bidding.[3] The single-mindedness assumption thus does not accommodate owners internalizing the benefits of multilicense ownership.

Our paper points to unintended consequences of the multilicense ownership that is prevalent in the data. In particular, the rules of the reverse auction leave room for strategic supply reduction by multilicense 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 percent of the acquired TV stations in the

[1] See "NRJ Wins Bidding for WSAH New York, But..." *TVNewsCheck*, November 29, 2011; "Small TV Stations Get Hot," *Wall Street Journal*, September 3, 2012; "Speculators Betting Big on FCC TV Spectrum Auctions," *Current*, 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.

[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.

reverse auction, off-loading another 54 percent 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 multilicense 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 naïve bidding with the outcome under strategic bidding when we account for the ownership pattern in the data and allow multilicense 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 repurposing 126 MHz of spectrum, the starting point of the incentive auction when it commenced on March 29, 2016, strategic bidding by multilicense owners increases nationwide payouts by 42.4 percent. For the 84 MHz clearing target that the incentive auction ultimately reached, strategic bidding increases nationwide payouts by 13.5 percent. These increases partly go to single-license owners, who as a group witness payout increases that are almost as large as those seen by multilicense 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 to equilibria that have significantly higher payouts than those under naïve bidding. Reaching these equilibria may thus not require widespread coordination of expectations between multilicense 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

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

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 United States and other countries as they strive to alleviate the "spectrum crunch" resulting from the rapid growth in data usage by smartphone 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 multilicense owners akin to an activity rule that eliminates the ability of multilicense 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 multilicense owners to exploit the joint ownership of TV stations, mitigates the payout increase from strategic bidding by between 71 percent and 89 percent, 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 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 multiunit 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.

[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.

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 multiunit auctions (Wilson 1979; Back and Zender 1993, 2001; Engelbrecht-Wiggans and Kahn 1998; Ausubel et al. 2014) that we come back to in Section II 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 2022; 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 I provides background on the FCC incentive auction. Section II provides a model of the reverse auction and strategic supply reduction. Sections III and IV present data and descriptive evidence in support of ownership concentration and strategic supply reduction. Section V describes our large-scale valuation and simulation exercise. Section VI quantifies the impact of ownership concentration and strategic supply reduction on the reverse auction. Section VII 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 VIII concludes.

I. 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 United States as of 2012 each hold a license to a 6 MHz block of spectrum in a particular geographical area dedicated to over-the-air transmission of programming.[6] Yet, only about 10 percent 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

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

[7] See *Connecting America: The National Broadband Plan*, FCC, 2010, chapter 5, p. 89.

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 United States.[8]

Reverse Auction.—The reverse auction uses a descending-clock format that we describe in detail in Section II. The FCC initially declared 2,197 TV stations as eligible for the reverse auction but then revoked the licenses of 3 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 noncommercial 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 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 repurpose its license for a new use, such as wireless service. The FCC assigns each TV station to a local media market called a designated market area (DMA region, henceforth, DMA for brevity). A DMA is defined by Nielsen Media Research

[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 August 3, 2017.

[9] See http://wireless.fcc.gov/auctions/incentive-auctions/Reverse_Auction_Opening_Prices_111215.xlsx, accessed 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.

[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 June 22, 2023.

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 United States 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 6 states (Connecticut, New Jersey, New York, Massachusetts, Pennsylvania, and Rhode Island), whereas the New York, NY, PEA consists of 42 counties in 4 states (Connecticut, New Jersey, New York, and Pennsylvania). 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 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]

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

[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.

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 US 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]

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 percent of the $10.1 billion payout, followed by the Los Angeles, CA, DMA with 13.2 percent and the Philadelphia, PA, DMA with 10.4 percent. Overall, 10 DMAs account for 75.5 percent 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

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

[15] See https://www.fcc.gov/news-events/blog/2013/12/06/path-successful-incentive-auction-0, accessed November 15, 2015, and "F.C.C. Delays Auction of TV Airwaves for Mobile," *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's TV Airwaves Auction Nears End with About $18 Billion in Bids," *Wall Street Journal*, January 18, 2017 (https://www.wsj.com/articles/fcc-sees-muted-demand-at-tv-airwaves-auction-1484754898)

[17] See "FCC Announces Repack Complete, Spectrum Open for Wireless," *TV Tech*, July 14, 2020.

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

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 show that 1,029 out of 2,194 auction-eligible TV stations participated in the reverse auction. Our ownership data for the continental United States show that, contrary to the FCC's expectations of low participation by sentimental owners, participation was higher among independently owned TV stations (54.09 percent) than among TV stations that are part of a chain (39.65 percent).

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 VA. 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 VIB.

II. 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 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,

[19] See https://tvnewscheck.com/uncategorized/article/wheeler-auction-once-in-a-lifetime-chance/ and "FCC Can Auction Spectrum, but Will Broadcasters Sell?" *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.

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

[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 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.

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; that is, $A_1 = \{1, \ldots, N\}$, $I_1 = \varnothing$, and $F_1 = \varnothing$. The reverse auction concludes after round τ if the base clock price reaches zero or no active TV stations remain, that is, if $P_{\tau+1} = 0$ or $A_{\tau+1} = \varnothing$.[25]

The auction design ensures that the FCC is able to assign a channel to any TV station that 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 $j' \in A_\tau \backslash \{j\}$ in round $\tau + 1$. If, as a consequence of TV station j withdrawing, the FCC cannot guarantee a channel for TV station j', that is, 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

[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 indicate that it cannot, and *TIMEOUT* to indicate that it has not succeeded in ascertaining feasibility in a preallotted 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 $P_{\tau+1} = 0$.

[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 tiebreaking 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.

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 Supplemental Appendix B.B3, 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.

A. *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 $b_j = v_j/\varphi_j$ as naïve bidding, and to $s_j = v_j/\varphi_j$ as the "score" of TV station j.

We use an example to illustrate that a firm owning multiple TV stations may have an incentive to deviate from naïve bidding. Hence, naïve 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 ($s_j = v_j/\varphi_j$)
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; that is,

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

[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).

Under naïve 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, naïve 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 naïve 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 VIIB.

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 $s_j = v_j/\varphi_j$ 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 naïve bidding. Firm 1's profit under naïve 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 naïve 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.

B. *Multiple Equilibria*

While strategic supply reduction is part and parcel of the reverse auction, our example admits multiple equilibria. In Supplemental Appendix B.B1, we show that the set of equilibria is

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

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 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 $b_j \in \left\{s_j, 900\right\}$ 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.

[29] The equilibria in 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, 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.

These restrictions on jointly owned TV stations are not overly arduous. In Supplemental Appendix B.B2, 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 Supplemental Appendix G.G2, 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.

III. 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 Supplemental Appendix C. Then we turn to the interference constraints on the repacking process.

A. *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, nonbroadcast revenue, and fixed cost, as detailed in Section VA.[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 percent of station-year observations,

[30] Outside estimates suggest that in 2016 advertising revenue accounts for 69 percent of a typical TV station's revenue, with a further 24 percent of revenue coming from retransmission fees and 7 percent coming from online activities. See "Retrans Revenue Share Expands in Latest US TV Station Industry Forecast," S&P Global Market Intelligence, July 14, 2016.

and we impute it as detailed in Supplemental Appendix C.C1. For noncommercial stations, including dark stations, advertising revenue is missing for 99.2 percent of station-year observations, and we do not impute it. We return to the distinction between commercial and noncommercial stations in Section VA.

The BIA data exclude nonbroadcast revenue, most notably retransmission fees that TV stations charge pay-TV providers to use their content.[31] To get at nonbroadcast revenue and fixed cost, we use the NAB data. As detailed in Supplemental Appendix C.C2, for commercial full-power stations, NAB collects financial information. Revenue is broken down into detailed source categories from which we are able to construct nonbroadcast 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 VA, 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.

B. *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 II.

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 percent, meaning that a TV station's population served cannot decrease by more than 0.5 percent in the repacking process. For an interference level of 0.5 percent, 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 percent standard. We also trace out how the ease of repacking as

[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 (https://www.streamtvinsider.com/cable/snl-kagan-raises-retrans-fee-forecast-to-9-8b-by-2020-mediacom-s-ceo-complains-to-fcc).

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

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

parameterized by the interference level affects the outcome of the reverse auction. In Section VIIB we rely on the pairwise interference files for an alternative, looser, standard of 2 percent that the FCC considered and for a very relaxed 10 percent standard.[34]

IV. Descriptive Evidence

We provide descriptive evidence in support of ownership concentration and strategic supply reduction. From here on, 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.

A. *Ownership Concentration*

Our data show 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 1 TV station across the United States, 66 hold 2 TV stations, 33 hold 3 TV stations, and the remaining 81 owners hold at least 4 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 1 multilicense owner, meaning that at least 2 TV stations within the DMA are jointly owned. Our analysis of the reverse auction focuses on multilicense ownership within DMA; we come back to multilicense ownership across DMAs in Section VIB.

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 hypothetical 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 half 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 multilicense 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 half of Table 1 reinforces that ownership is more concentrated in positive demand DMAs. In 80 of 119, or 67 percent (54 of 79, or 68 percent) of positive demand

[34] The FCC developed a piece of software, *TVStudy*, 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 March 7, 2018).

[35] Out of the 145 TV stations that went off the air, 7 are located in Puerto Rico. These 7 TV stations together claimed less than 0.5 percent of payouts in the reverse auction. The 480 auction-eligible VHF stations together claimed a mere 3.7 percent of payouts in the reverse auction.

[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.

Table 1—Ownership Concentration

DMAs:	All	Positive demand at 120 MHz	Positive demand at 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 multilicense owners	1.25	1.40	1.53
Percentage of DMAs with j multilicense 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
Number of DMAs	202	119	79

DMAs for the 120 MHz (84 MHz) clearing target, there is at least 1 multilicense owner, relative to 124 of 202, or 61 percent of all DMAs. Taken together, this shows that multilicense 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 noncommercial full-power stations in the DMA. However, these rules are oriented toward 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 noncommercial, low-power, and satellite stations, and waivers can be—and have been—granted for failing or financially 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 multilicense ownership.

B. *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 Supplemental Appendix D. Of the 48 TV stations, 15 are full-power stations, and 33 are low-power class A stations; 47 are commercial stations, and 1

[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 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 March 29, 2018).

is a noncommercial 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 4 TV stations in the Los Angeles, CA, DMA, and OTA acquired 11 TV stations in the Pittsburgh, PA, DMA. The 10 TV stations acquired by LocusPoint are located in 10 different DMAs, as are the 15 TV stations acquired by NRJ and the 23 TV stations acquired by OTA. In Supplemental Appendix D.D2, we show that the 48 TV stations acquired by the 3 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 percent of the acquired TV stations, in the reverse auction and sold another 26 TV stations, or 54 percent 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 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 percent for LocusPoint to 200 percent for NRJ to 509 percent for OTA.[38]

While the activities of the 3 private equity firms are very salient, their contribution to ownership concentration is small: the private equity firms are just 3 of 180 owners, or 2 percent, that hold more than one TV station across the United States, and they hold just 48 of 1,368 TV stations, or 4 percent, 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.

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

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 ($ millions)	55.85	15.19	27.00
Profit/loss ($ millions)		8.79	−19.40
NRJ			
Number	15	7	7
Amount ($ millions)	245.26	640.49	94.45
Profit/loss ($ millions)		527.22	−3.50
OTA			
Number	23	10	12
Amount ($ millions)	78.70	440.68	38.38
Profit/loss ($ millions)		401.99	−1.64

V. 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 Supplemental 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.

A. *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 $v_{jt_0}^{CF}$ and its "stick" value $v_{jt_0}^{Stick}$:

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

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

[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," by Mark Mondello and Arya Rahimian (Duff and Phelps, November 23, 2015).

a noncommercial 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

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

where $\alpha(X_{jt};\beta)AD_{jt}$ is the contribution of advertising revenue to cash flow; $RT(X_{jt};\gamma)$ is nonbroadcast revenue including retransmission fees; $F(X_{jt};\delta)$ is fixed cost; and $\epsilon_{jt} \sim N(0,\sigma^2)$ 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 $\alpha(X_{jt};\beta)$, $RT(X_{jt};\gamma)$, and $F(X_{jt};\delta)$ and estimate the parameters $\boldsymbol{\theta} = (\beta,\gamma,\delta,\sigma)$ drawing on the aggregated data from NAB.

We use a simulated minimum distance estimator. The parameters $\boldsymbol{\theta} = (\beta,\gamma,\delta,\sigma)$, 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, nonbroadcast 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 nonbroadcast 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

[40] Any cable operator offering more than 12 channels must set aside one-third of its channels for local commercial broadcasters. Any cable operator offering more than 36 channels must carry all noncommercial and educational broadcasters.

reported by NAB is between 0.97 and 0.99 for cash flow, 0.95 for nonbroadcast 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 noncommercial stations, and 4 dark stations that we henceforth subsume into noncommercial 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 noncommercial 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] As specified in equations (4)–(7), the reservation value $\hat{v}_{jt_0}$ of a commercial station is then the higher of the realized draws of its cash flow value and its stick value; the reservation value $\hat{v}_{jt_0}$ of a noncommercial 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.

[41] See Bond and 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 are 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 Supplemental Appendix A.A2.

Validation.—To validate our estimated reservation values and to provide further evidence of strategic supply reduction, we use the recently released data that record 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 United States. 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 United States. For the sample of cash flow–valued stations, the coefficient on the constant as expected approaches zero, and the coefficient on the estimated reservation value approaches one as we narrow the set of TV stations. This is not the case for the sample of stick-valued stations, although our estimated reservations values are strongly positively correlated with the dropout points.

We conclude that our estimated reservations values are, on average, informative about true reservation values as given by the dropout points of independently owned TV stations, especially for cash flow–valued stations. At the same time, our estimated reservation values can differ considerably from the dropout points for individual TV stations.[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 are available on noncommercial 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.

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

[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.

[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 an outlier from the sample of cash flow–valued stations in Table 3.

Table 3—Regression of Dropout Points on Constant and Estimated Reservation Values

		No shared owner		
	All	Within DMA	Within DMA and neighbors	Across US
Panel A. Cash flow–valued stations				
Constant	26.81	12.95	10.97	7.389
	(3.245)	(4.356)	(4.645)	(6.203)
Estimated reservation value	0.690	1.561	1.101	1.141
	(0.059)	(0.113)	(0.129)	(0.227)
Adjusted R^2	0.206	0.362	0.286	0.207
Observations	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 reservation value	4.249	4.665	3.378	8.263
	(0.495)	(0.519)	(0.748)	(1.216)
Adjusted R^2	0.273	0.341	0.197	0.480
Observations	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

B. *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 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 barred 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

[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, https://apps.fcc.gov/edocs_public/attachmatch/DA-16-453A1.pdf (accessed March 7, 2018). The FCC additionally declared KLHU-CD as not needed but revoked its license prior to the reverse auction; see footnote 9.

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 I, 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 toward 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 Supplemental Appendix E, we show that a region is generally much larger than a DMA. On average, a region covers about 11 DMAs and has about 19 times as many TV stations as 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 naïve bidding, where we ignore the 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 $b_j = s_j = v_j/\varphi_j$, where v_j is its reservation value and φ_j its broadcast volume. We simulate the reverse auction under naïve bidding for $N^s = 100$ draws of reservation values. In Supplemental Appendix F, we provide pseudo code for our algorithm.

We contrast naïve 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 $b_j = s_j$

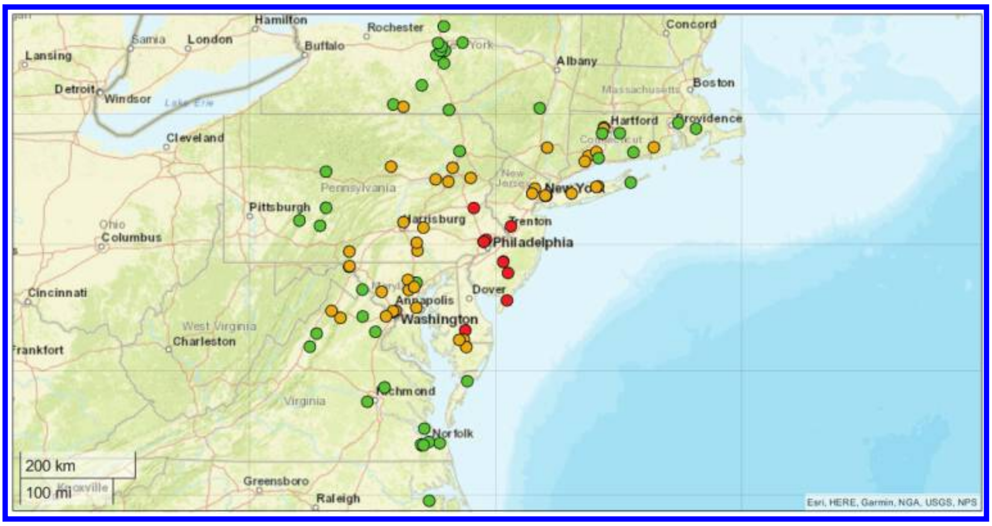

FIGURE 1. REPACKING REGION FOR PHILADELPHIA, PA, DMA

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.

(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 multilicense ownership across DMAs; we come back to it in Section VIB.

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 preassign to frozen status any TV station located outside the focal DMA that has been frozen at the conclusion of the reverse auction under naïve bidding; these TV stations therefore cannot freeze another TV station. In Supplemental Appendix F, we provide pseudo code for the modified algorithm.

This modification significantly reduces the computational burden.[49] In Supplemental Appendix G.G1, we show that nationwide payouts under naïve 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 multilicense owner have more than

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

[49] Under naïve 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.

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 multilicense 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 VI.

VI. 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.

A. *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 naïve 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 naïve bidding in panel A and under two equilibria with strategic bidding in panels B and C.[50] All panels show reservation values and payouts (in millions of dollars) 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 multilicense ownership using symbols to distinguish between owners.

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

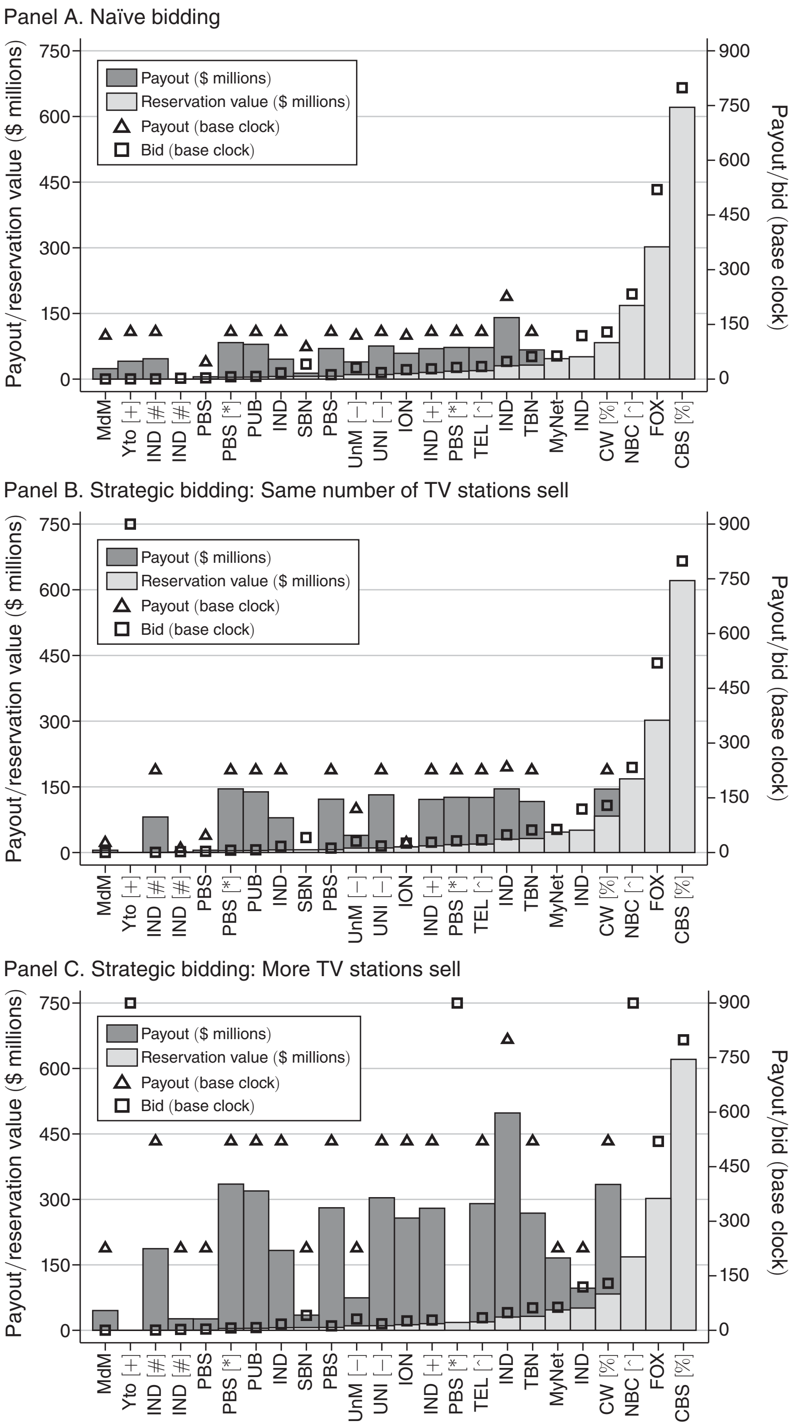

Figure 2. Sample Outcome for Philadelphia, PA, DMA, 126 MHz Clearing Target

Naïve Bidding.—Panel A of Figure 2 shows the outcome under naïve bidding. Seventeen 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 naïve 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 multilicense owners can lead to the same number of TV stations being sold as under naïve 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 naïve bidding, NRJ thus forgoes a payout of $40.87 million, translating into a forgone 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 naïvely. Overall, the same number of TV stations sell as under naïve 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 [^]) withholds the NBC affiliate WCAU, one of the two TV stations it owns. Nevertheless, more TV stations sell than under naïve 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 naïve 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 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 1 to 11. 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.

Table 4—Payouts to TV Stations Nationwide and by Owner Type

Payouts ($ billions)	Naïve bidding	Strategic bidding				Payout increase at mean (%)
		Mean	Min	Median	Max	
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)	
Multilicense 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)	
Multilicense 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 multilicense 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 naïve bidding.

B. *Nationwide Payouts in the Reverse Auction*

In comparing the outcomes of the reverse auction under naïve 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 naïve and strategic bidding, first nationwide and then broken down for single- and multilicense 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

[51] The existence of a pure strategy equilibrium under strategic bidding is not guaranteed. In addition, as described in Section VB, we discard equilibria that entail a failure at the outset. As a result, in 0.03 percent of runs of the reverse auction, corresponding to 6 simulations in 4 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 percent 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 naïve bidding.

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

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 percent, and by \$0.334 billion from \$2.478 billion to \$2.812 billion for the 84 MHz clearing target, an increase of 13.5 percent.

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 multilicense owners. The payout increase from strategic bidding for multilicense owners is 46.1 percent and 14.5 percent under the 126 MHz and 84 MHz clearing targets, respectively. As in our case study of the Philadelphia, PA, DMA in Section VIA, this spills over to single-license owners, who do not engage in strategic supply reduction but see a payout increase of 40.5 percent or 12.9 percent depending on the clearing target.

As in the actual reverse auction (see Section I), payouts are concentrated in a small number of DMAs. Under the 84 MHz clearing target, the Los Angeles, CA, DMA accounts for 37.8 percent of the \$2.812 billion payout, followed by the New York, NY, DMA with 14.8 percent and the Philadelphia, PA, DMA with 11.9 percent. Overall, 10 DMAs account for 83.3 percent 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 percent of the \$0.334 billion gains, followed by the Philadelphia, PA, DMA with 15.3 percent and the New York, NY DMA with 12.6 percent. Overall, 10 DMAs account for 96.4 percent of the \$0.334 billion gains.[53]

We further investigate the sources of the gains from strategic bidding in Table 5. The left side lists the gains for the 10 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 naïve 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 naïve bidding ("no longer selling"). Across the 10 DMAs, TV stations that sell under both naïve and strategic bidding account for between 20.1 percent and

[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 5—Decomposition of Payout Gains from Strategic Bidding in 10 DMAs by Type of TV Station, 84 MHz Clearing Target

	Payout change ($ billions)				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	1,670	177.719	12.729	7.521

Notes: Payout change due to strategic bidding calculated as difference between mean payouts under strategic and naïve bidding. For a given simulation draw and payout-unique equilibrium, we classify a TV station as always selling if it sells under both naïve and strategic bidding, as newly selling if it sells only under strategic bidding, and as no longer selling if it only sells under naïve bidding.

104.6 percent of the payout increases due to strategic bidding. Taking the 10 DMAs together, TV stations that sell under both naïve and strategic bidding account for 83.5 percent of the $0.322 billion gains.

The right side of Table 5 shows the number of TV stations in the 10 DMAs (“total”) and a decomposition into the 3 categories.[54] Taking the 10 DMAs together, 73.48 or 90.6 percent of the $73.48 + 7.65 = 81.13$ TV stations that sell under strategic bidding also sell under naïve 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 VIA. 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 naïve 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 naïve 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

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

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)

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 withdrawing TV stations among these 498 TV stations is small: it amounts to 38.69 or 7.8 percent under the 126 MHz clearing target and to 29.36 or 5.9 percent 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 naïve 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 percent of the 1,670 TV stations. Under naïve bidding and the 84 MHz clearing target, on average across simulation draws, their TV stations set the

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

price for 15.34 other TV stations, or for 9.55 percent of all frozen TV stations. As we mention in Section IVB, 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 percent and 39.1 percent of the overall holdings of NRJ and OTA.

Not surprisingly, the private equity firms benefit significantly from the reverse auction. As described in Section IVB, the private equity firms relinquished only 19 TV stations, or 40 percent of the acquired TV stations, in the actual reverse auction. Specifically, NRJ relinquished 2 TV stations, NRJ 7 TV stations, and OTA 10 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 naïve bidding on 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 percent to 25.3 percent across firms.

Model Fit.—As noted in Section VA, 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 naïve 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 I), 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 0 payout with a probability of 0.86 on average across simulation draws under the 84 MHz clearing target and either naïve 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 0 payout conditional on the DMA actually having a 0 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 naïve or strategic bidding, whereas in the actual reverse auction, payouts were highest in the New

Table 7—Private Equity Firms' Payouts and Sales of TV Stations, 84 MHz Clearing Target

	Naïve bidding		Strategic bidding		Payout increase at mean (%)
	Number TV stations sold	Payout ($ millions)	Number TV stations sold	Payout ($ millions)	
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)	

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

York, NY, DMA, followed by the Los Angeles, CA, and Philadelphia, PA, DMAs.[56] Moreover, payouts in the actual reverse auction amounted to $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 I). The recently released data show that only 898 or 53.77 percent of the 1,670 TV stations participated in the reverse auction. We relax the assumption of full participation and use these data to set the bid of a nonparticipating TV station to $b_j = 900$. Table 8 shows the resulting payouts to TV stations under naïve 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 percent.

[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.

[57] In 0.04 percent 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 naïve bidding. While the reverse auction does not fail at the outset under naïve 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.

TABLE 8—PAYOUTS TO TV STATIONS NATIONWIDE UNDER REALIZED PARTICIPATION

Payouts ($ billions)	Naïve bidding	Strategic bidding				Payout increase at mean (%)
		Mean	Min	Median	Max	
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 naïve bidding. Using $N^S = 50$ simulation draws for Pittsburgh, PA, DMA under 84 MHz clearing target.

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 VA), 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.

Multimarket Strategies.—Strategic bidding may extend beyond market boundaries if multilicense 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 IVA, cross-market multilicense ownership is pronounced. We illustrate how multimarket strategies may work, continuing with the Philadelphia, PA, DMA as a case study in the interest of computational tractability.

As we detail in Supplemental Appendix H, 12 of the 18 owners hold at least 1 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 multimarket 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 percent under the 84 MHz clearing target, on average across payout-unique equilibria and simulation draws. The fact that accounting for a single case of cross-market multilicense 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.

C. *Efficiency Losses from Strategic Bidding*

There are efficiency losses from strategic bidding by multilicense 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 repurposed 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 values of acquired TV stations under naïve and strategic bidding are very similar. This reflects in part that roughly the same number of TV stations sell in the reverse auction under naïve and strategic bidding, averaging across simulation draws to 185.24 under naïve 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 Supplemental 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 10 DMAs in terms of payouts in the actual reverse auction. Overall, the auction design is close to efficient, thereby limiting the scope for further efficiency gains from redesigning 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 repurposed 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 I). 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]

VII. Mitigating the Impact of Ownership Concentration

In Section VI, we have shown that strategic bidding by multilicense 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 multilicense 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.

[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 naïve bidding and 466.23 under strategic bidding.

[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 Multilicense Owners

Payouts ($ billions)	Naïve 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)	

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

A. *Restriction on Multilicense Owners*

The discussion in Section IIA 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 multilicense 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 percent and 89 percent less than in Table 4, depending on the clearing target. The rule change mitigates payout increases by requiring that multilicense 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.

B. *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 IIIB. While the FCC settled on a 0.5 percent interference level, the alternative, looser standards of 2 percent and 10 percent would have eliminated some interference constraints on the repacking process and thus made TV stations more substitutable.

To understand the role of the interference level and the implied degree of substitutability, we simulate the reverse auction for the Philadelphia, PA, DMA under 12 different scenarios. Each scenario pairs 1 of the 3 interference levels (0.5 percent, 2 percent, and 10 percent) with 1 of the 4 clearing targets (126 MHz, 114 MHz, 108 MHz, and 84 MHz) that the FCC considered. Under these 3 interference levels, the average number of interference constraints for a TV station in the Philadelphia, PA,

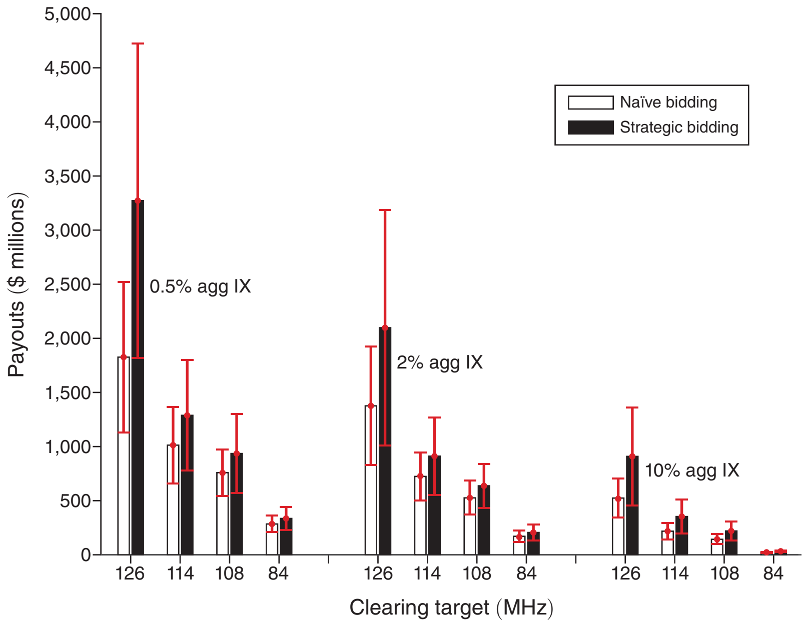

Figure 3. Payouts to TV Stations in Philadelphia, PA, DMA under Alternative Interference Levels and Clearing Targets

DMA drops from 62.96 for the 0.5 percent interference level to 48.88 and 32.63 for the 2 percent and 10 percent interference levels, respectively. The results are shown in Figure 3, where we display payouts (in millions of dollars) under naïve bidding as white bars and payouts under strategic bidding as black bars, with 95 percent 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 multiunit auctions in wholesale electricity markets (e.g., Wolfram 1998; Hortacsu and Puller 2008). Borenstein, Bushnell, and Wolak (2002) note that the effect of such an exercise of market power can be large when demand or supply is inelastic. In contrast to electricity, TV stations are not homogeneous in the repacking process because of interference constraints. We show that product differentiation amplifies the impact of strategic supply reduction, even though the FCC's demand for TV stations is elastic. Our results thus complement the earlier literature by highlighting the interaction of product differentiation and strategic supply reduction.

VIII. Conclusions

In this paper, we explore the implications of ownership concentration for the recently concluded incentive auction that repurposed 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 the data with the outcome under naïve bidding. Naïve 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 multilicense owners increases nationwide payouts by 42.4 percent on average; for the 84 MHz clearing target, strategic bidding increases nationwide payouts by 13.5 percent.

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 multilicense 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 naïve 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 repurposed 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

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

and investigate how placing a restriction on the bids of multilicense 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 repurposing spectrum toward more efficient uses.

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