Supply Reduction in the Broadcast Incentive Auction*

Christina Aperjis†, Lawrence M. Ausubel‡ and Oleg Baranov§

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Abstract

The FCC's Broadcast Incentive Auction incorporated a reverse auction for the voluntary clearing of broadcast stations. While aiming to be obviously strategy-proof, it maintained the fiction that stations were owned individually when many were part of station groups. Theoretically, this design creates severe supply-reduction incentives in stylized models, while alternative Vickrey-Clarke-Groves-based mechanisms would avoid these incentives yet still enable price discrimination. Empirically, the first analysis of the actual bidding data—matched with *ex post* resale data—reveals unmistakable instances of drop-out prices far exceeding station values. Both theoretically and empirically, supply reduction posed a serious challenge to the reverse auction.

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† Power Auctions LLC, 3333 K St NW Suite 425, Washington, DC 20007, USA. Email: aperjis@powerauctions.com

‡ Department of Economics, University of Maryland, College Park, MD 20742, USA. Email: ausubel@econ.umd.edu

§ Department of Economics, University of Colorado, Boulder, CO 80309, USA. Email: oleg.baranov@colorado.edu

The Broadcast Incentive Auction (BIA) conducted by the Federal Communications Commission (FCC) in 2016–17 has received greater attention than any other spectrum auction of the past 15 years. The reason for this heightened interest was that, while market-based mechanisms for the allocation of spectrum licenses have been a prominent feature of the telecommunications landscape for 25 years, such mechanisms have generally taken the spectrum's use as given and have sought to allocate licenses efficiently. By contrast, the BIA addressed a situation where the spectrum was already being used (for television broadcasting) and the incumbents held property rights in the current use, but there was an opportunity to repurpose the spectrum for a higher-value use (mobile broadband). As such, the Broadcast Incentive Auction integrated a reverse auction for the voluntary clearing of broadcast stations and a forward auction for the sale of mobile broadband licenses directly into the allocation mechanism.

This paper focuses on the incentive properties of the Incentive Auction's reverse auction. While the reverse auction aimed to be obviously strategy proof (Milgrom and Segal, 2019), it maintained the fiction that stations were owned individually, when many were part of station groups. This created the possibility of supply reduction, the mirror image of the well-known phenomenon of demand reduction in uniform-price auctions (Ausubel et al., 2014). Vulnerability to supply reduction could lead both to inefficient clearing of incumbent stations and increased clearing costs (Doraszelski et al., 2017). Inefficient clearing is of concern for all of the usual reasons; increased clearing costs are of concern, even from an efficiency perspective, because it could reduce the quantity of spectrum repurposed via the BIA below the constrained-efficient level.

In Section 2 of this paper, we introduce two stylized models of the Broadcast Incentive Auction's clearing environment that are useful for understanding the problem. They yield the same feasibility constraint and, therefore, are equivalent for studying the problem. In Section 3, we describe a Deferred Acceptance auction, an individual ownership weighted VCG mechanism, and a joint ownership bidder-weighted VCG mechanism. The first two are closely related to one another and to the reverse auction that was actually conducted, while the third has very different (and potentially superior) incentive properties. In Section 4, in a special case of the stylized model, we construct equilibria of both the Deferred Acceptance auction and the joint ownership bidder-weighted VCG mechanism. In particular, in equilibria of the Deferred Acceptance auction, station groups drop out in some of their stations at the opening price. In Section 5, we provide the first analysis that has been done of the Incentive Auction's bidding data. The bidding data, together with *ex post* resale data, provide evidence of supply reduction. In particular, Table 3, detailing OTA Broadcasting's bidding in the Pittsburgh market, may provide the most compelling empirical evidence of supply (or demand) reduction in the literature to date.

1. The Reverse Auction and its Susceptibility to Supply Reduction

The reverse auction of the Broadcast Incentive Auction was a procurement mechanism for purchasing television licenses from broadcasters so that the spectrum could be repurposed for mobile broadband. This section begins by providing a high-level description of the reverse auction mechanism, stripped of all but its bare essentials.[1]

[1] For example, the actual Broadcast Incentive Auction included three possible actions by a UHF station: relinquish, move to Low-VHF, and move to High-VHF. In the current description, we will suppress inessential details and describe the BIA as only allowing the relinquish move, as this is sufficient to discuss the issue of supply reduction.

By entering the auction, a broadcast station committed itself to relinquish its license, if required, in return for a pre-specified opening price. Then, in successive rounds, the participating station would be presented with a descending sequence of prices. Each round, each remaining station was given the choice whether it was willing to relinquish its license in return for the next lower price in this sequence, or whether it preferred to exit the auction. Exit was irrevocable. After the round, bids were processed sequentially. Before a station's bid would be processed, the auction system checked whether it was still feasible for the station to exit, i.e., whether the remaining stations (both those that had already exited and those that had chosen not to participate in the auction) could be fit into the available spectrum without violating any interference constraints. Once a station's exit became infeasible, the price would no longer be reduced for that station and the station would be required to relinquish at the price corresponding to its last processed bid; any pending bid by this station would now not be processed.

The auction was driven by a single descending clock, scaled differently for each station. The opening prices varied station by station, and depended on a measure of the interference that the station caused to other stations and on the station's interference-free population. The percentage price reductions in subsequent rounds were the same across all stations.

If all stations had been licensed to broadcast from the same tower and at the same power level, all stations would have had the same opening prices and the auction format would have collapsed to a uniform-price auction. In a descending uniform-price auction for discrete goods, each bidder offering a single unit finds it optimal to remain in the auction so long as the price exceeds its value and to exit as soon as the price drops below its value. However, bidders offering two or more units have the incentive to engage in supply reduction. The intuition is simply the monopolist's incentive to reduce its quantity in order to obtain a higher price for the units that it would sell anyway. This gives rise to an inefficiency theorem that, with few exceptions, equilibrium outcomes must be *ex post* inefficient (Ausubel et al., 2014). When stations are licensed to broadcast from different locations and/or at different power levels, it is easy to see that a single-station bidder still finds truthful bidding to be optimal. By the same token, the incentives for supply reduction persist for multi-station bidders, especially for bidders owning two or more stations whose signals would interfere with one another if they broadcast on the same channel.

1.1 The extent of multi-station ownership

Empirically, more than two-thirds of the stations entered into the reverse auction were bid by groups of two or more stations. Of the 930 UHF stations entered into the auction, 637 were bid by groups controlling two or more stations. The three station groups with the largest number entered in the auction were ION Media (56 stations), Nexstar Broadcasting (51 stations) and Sinclair Broadcast Group (31 stations). The frequency distribution of the number of stations associated with each bidder is shown in Table 1.

Table 1. Frequency Distribution of Station Groups

Number of Stations Controlled by Bidder	Frequency
50+	2
40 – 49	0
30 – 39	1
20 – 29	3
10 – 19	9

5 – 9	23
2 – 4	70
1	293

1.2 Supply and demand in the tightest markets

The BIA sought to repurpose a uniform amount of bandwidth nationally, ultimately 84 MHz of spectrum. Meanwhile, the number of incumbent stations and the ability to compress their spectrum usage without relinquishment varied widely. Effectively, market power at the local market level varied widely.

The standard market area used in the United States for broadcasting is the designated market area (DMA), the geographic area in which local television viewing is measured by Nielsen. Table 2 displays the number of stations entered in the auction, the number of stations ultimately relinquished and the ratio of relinquished / entered, for the 20 DMAs where this ratio was the highest. The number of stations relinquished was not a hard requirement, as there was some substitutability among stations in different DMAs in the clearing. However, as can be seen in the last column of Table 2, a high ratio of relinquished / entered was often reflected in a high payment for relinquishment. For example, the three stations in the Harrisburg-Lancaster-Lebanon-York DMA fetched an average of $80 million each, despite having only 715,000 TV homes (only one-tenth the number in the New York DMA).

Table 2. 20 DMAs with the Tightest Supply-Demand Balances

Designated Market Area (DMA)	# of Stations Entered	# of Stations Relinquished	Relinquished / Entered	Average Payment for Relinquishment
Harrisburg-Lancaster-Lebanon-York, PA	3	3	100.00%	$80,869,209
Dayton, OH	3	2	66.67%	$23,692,520
Greenville-Spartanburg, SC-Asheville, NC	3	2	66.67%	$44,379,054
Lansing, MI	3	2	66.67%	$13,759,418
Washington, DC	15	8	53.33%	$71,650,283
Harrisonburg, VA	4	2	50.00%	$15,967,121
Hartford-New Haven, CT	8	4	50.00%	$66,158,854
New York, NY	20	10	50.00%	$141,807,262
Rockford, IL	2	1	50.00%	$50,060,965
Philadelphia, PA	21	10	47.62%	$104,454,558
Boston, MA	15	7	46.67%	$92,377,724
Milwaukee, WI	9	4	44.44%	$78,813,420
San Francisco-Oakland-San Jose, CA	19	8	42.11%	$84,466,661
Chicago, IL	15	6	40.00%	$126,323,988
Providence, RI-New Bedford, MA	5	2	40.00%	$79,869,952
San Diego, CA	5	2	40.00%	$29,358,795
Los Angeles, CA	23	9	39.13%	$108,710,250
Charlotte, NC	8	3	37.50%	$34,751,468
Cleveland-Akron, OH	11	4	36.36%	$25,860,592
Pittsburgh, PA	20	7	35.00%	$14,970,471

Washington DC, New York, Philadelphia and Boston appeared to be the large markets with the tightest supply-demand conditions: in each, 7 to 10 stations were needed, and only about twice as many stations had been entered in the auction. San Francisco-Oakland-San Jose, Chicago and Los Angeles were only slightly looser, with 6 to 9 stations needed and approximately 2 ½ times as many stations available.

2. Two Models of the Reverse Auction

This section describes two stylized models of the reverse auction. While the first model assumes one tower and the second model assumes two towers, they will yield identical feasibility constraints.

2.1 The Single Tower model

There is a single city, and all stations transmit from the same tower.[2] There are two types of television stations, with the following associated interference patterns:

- *Full-power stations*: If a full-power station is situated on a given television channel, no other station can use the same or an adjacent channel.
- *Low-power stations*: If a low-power station is situated on a given television channel, no other station can use the same channel, but another low-power station can use an adjacent channel.

There are currently n_H full-power stations and n_L low-power stations in total transmitting from the tower. The auctioneer is running an auction in order to "repack" these stations into just $2k$ television channels.[3] The channels are ordered in the natural way from 1 to $2k$, so that channels c and d are adjacent if and only if $|c - d| = 1$. The stations view all $2k$ channels as equivalent.

Since this is a reverse auction, the "winners" in the auction are those stations that win the competition to relinquish their broadcast licenses and are paid the relevant clearing price. The "losers" in the auction are those stations that lose the competition to relinquish their licenses, retaining their broadcast licenses and remaining on-air. Let m_H ($0 \le m_H \le n_H$) and m_L ($0 \le m_L \le n_L$), respectively, denote the number of full-power stations and low-power stations that remain on-air. The feasibility constraint in the Single Tower model is thus:

$$2m_H + m_L \le 2k\,. \tag{1.1}$$

[2] Chicago comes extremely close to satisfying this assumption: all Chicago stations transmit from either 875 North Michigan Avenue (the building formerly known as the John Hancock Building) or the Willis Tower (the building formerly known as the Sears Tower). These two 100+ story broadcast towers are less than two miles apart. Similarly, most major stations in the Los Angeles DMA transmit from Mount Wilson, and the remaining stations broadcast from the adjacent Mount Harvard.

[3] We limit our attention to even integer numbers of channels, as this is required to make the feasibility constraints of the Single Tower and the Two Towers models the same.

2.2 The Two Towers model[4]

There are two cities, located sufficiently close to each other that a full-power station in one city would interfere with a station on the same channel in the other city.[5] All stations in a given city transmit from the same tower.[6] Thus, there are two towers. There are two types of television stations, with the following associated interference patterns (somewhat different interference patterns are assumed than in the preceding Single Tower model):

- *Full-power stations*: If a full-power station is situated on a given television channel in one city, the same channel cannot be used in the other city.
- *Low-power stations*: Two low-power stations, one in each city, can co-exist on the same television channel.

There are currently n_H full-power stations and n_L low-power stations in total transmitting from the two towers. The auctioneer is running an auction in order to "repack" these stations into just k television channels. For the sake of simplicity, we will assume that the values of a given type of station in the two cities are drawn from the same distribution and that a low-power station remaining on-air is indifferent between being assigned to either tower (i.e., city).

As in the Single Tower model, the "winners" in the auction are those stations that win the competition to relinquish their broadcast licenses; the "losers" are those stations that retain their licenses. Again, let m_H ($0 \le m_H \le n_H$) and m_L ($0 \le m_L \le n_L$), respectively, denote the number of full-power stations and low-power stations that remain on-air. Observe that the feasibility constraint in the Two Towers model is exactly the same as in the Single Tower model, i.e., inequality (1.1).

2.3 Information Structure

All of the full-power stations j ($j = 1, \dots, n_H$) have values v_j to their current owners (in either city), where v_j is drawn from a common distribution $F(\cdot)$ with support $[0,\bar{v}]$. All of the low-power stations j ($j = n_H + 1, \dots, n_H + n_L$) have values v_j to their current owners (in either city), where v_j is drawn from a common distribution $G(\cdot)$ with support [0,1]. We will consider each of two possible information structures in this paper:

- *Perfect correlation*: All full-power stations have the same values, $v_1 = \dots = v_{n_H}$, and all low-power stations have the same values, $v_{n_H+1} = \dots = v_{n_H+n_L}$. The single draw of the full-power v and the single draw of the low-power v are independent.
- *Independence*: The values, $v_1, \dots, v_{n_H}$, of all full-power stations and the values, $v_{n_H+1}, \dots, v_{n_H+n_L}$, of all low-power stations are drawn independently.

In our analysis, we will be considering scenarios where two or more full-power stations are commonly owned and/or where two or more low-power stations are commonly owned. We examine the perfect

[4] The authors wish to acknowledge their gratitude to J.R.R. Tolkien for this terminology.

[5] The reader can think of New York and Philadelphia (slightly more than 80 miles apart) as examples of such cities.

[6] See footnote 2.

correlation information structure as it is the simplest to analyze; we examine the independence information structure as it may be regarded by the literature to be the most "natural". These information structures are the boundary cases of a family of information structures considered in a somewhat different context by Ausubel and Baranov (2019).

3. Reverse Auction Mechanisms

In this paper, we will consider a number of different possible mechanisms for the reverse auction.

3.1 Deferred Acceptance auction

Associated with each station j = 1, … , J is a *weight* $w_j > 0$. The starting price, $p_j(0)$, for station j is $w_j \overline{p}$, where $\overline{p}$ is chosen to be sufficiently large that $w_j \overline{p}$ is never less than the top of the support of v_j. At each later time, the prices of all stations drop continuously and proportionately. We write:

$$p_j(t) = w_j(1-t)\overline{p} \quad , \quad \text{for all } j = 1, \ldots, J \text{ and for all } t \in [0,1]. \tag{1.2}$$

There is a feasibility constraint associated with the clearing problem; the feasibility constraint is inequality (1.1) for the models of Section 1. Each station is initially "in" at the starting price and the feasibility constraint is initially satisfied. Each station has the choice at all times whether to remain in the auction or to exit, so long as its exit would not cause the feasibility constraint to be violated. Exit from the auction is irrevocable; following exit, the station retains its broadcast license and is paid zero. If station j remains "in", it faces a descending price of $p_j(t)$ at every time t. Station j is deemed to "win" at the first time, t_j, that its departure would cause the feasibility constraint to be violated. A winning station j relinquishes its broadcast license and is paid a price of $p_j(t_j)$.[7] In the event that two or more stations attempt to exit simultaneously, their exit requests are processed sequentially in a randomly-selected order, and each station's exit is permitted only if the feasibility constraint would continue to be satisfied without this station (and without all stations that have previously been allowed to exit).

When stations are individually owned, it is well understood that truth-telling is a dominant strategy of the Deferred Acceptance auction (Milgrom and Segal, 2019); moreover, the mechanism is obviously strategy proof (Li, 2017). Conversely, when two or more stations are jointly owned, the Deferred Acceptance auction is no longer a dominant strategy nor an obviously strategy proof mechanism.

In the specific models considered in this paper, there are only two types of stations. We let the weight of a low-power station be $w_L = 1$ and we let the weight of a full-power station be $w_H > 1$. The price equation (1.2) for the two types of stations, and using the lowest allowable value for $\overline{p}$, then reduces to:

$$p_H(t) = w_H(1-t)\max\left\{1, \tfrac{\overline{v}}{w_H}\right\} \quad , \quad p_L(t) = (1-t)\max\left\{1, \tfrac{\overline{v}}{w_H}\right\} \quad , \quad \text{for all } t \in [0,1]. \tag{1.3}$$

[7] In the Broadcast Incentive Auction, the state when a station's exit would cause the feasibility constraint to be violated was referred to as "frozen". A currently frozen station could be unfrozen at a later stage of the auction, when the number of channels is increased. However, in the current models being considered, the state of being frozen is irrevocable and therefore "frozen" is equivalent to "winning".

3.2 Individual ownership weighted VCG mechanism

The individual ownership weighted VCG mechanism is defined similarly to the standard VCG mechanism, except for: (1) the use of weights; and (2) the treatment of stations as individually owned, regardless of their actual ownership structure. It is developed as follows.

Each station $j = 1, \ldots, J$ reports a value, $\hat{v}_j$, representing the minimum payment that the station would accept in order to relinquish its license. Let $x_j = 1$, if a station "wins" in the auction (i.e., if the station is paid to relinquish its license), and $x_j = 0$, otherwise. Let $x = (x_1, \ldots, x_J)$ denote the allocation vector. The feasible set, X, is the set of all allocations satisfying the feasibility constraint, i.e., all allocation vectors x such that the set of stations retaining their broadcast licenses can be repacked into the available channels. As before, associated with each station $j = 1, \ldots, J$ is a *weight* $w_j > 0$. We let $\frac{1}{w}\hat{v}$ denote the weighted vector of value reports, i.e., $\frac{1}{w}\hat{v} = \left(\frac{1}{w_1}\hat{v}_1, \ldots, \frac{1}{w_J}\hat{v}_J\right)$. The auctioneer determines the outcome by computing a weighted value-minimizing allocation:

$$x^* \in \arg\min\left\{x \cdot \tfrac{1}{w}\hat{v} \mid x \in X\right\} \text{ and } \alpha = \min\left\{x \cdot \tfrac{1}{w}\hat{v} \mid x \in X\right\}. \tag{1.4}$$

Paralleling the development of the VCG mechanism, the auctioneer also minimizes value under the assumption that station j is absent from the auction (and station j retains its broadcast license):

$$\alpha_j = \min\left\{x \cdot \tfrac{1}{w}\hat{v} \mid x \in X \text{ and } x_j = 0\right\}. \tag{1.5}$$

The *individual ownership weighted VCG mechanism* is the mechanism that establishes the allocation x^* and pays p_j to each station such that $x_j^* = 1$, where:

$$\frac{p_j}{w_j} = \alpha_j - \left(\alpha - \frac{\hat{v}_j}{w_j}\right). \tag{1.6}$$

With weights $w_j = 1$, for all $j = 1, \ldots, J$, the weighted VCG mechanism coincides with the standard VCG mechanism when stations are individually owned—and therefore it is a dominant strategy mechanism. The usual VCG reasoning implies the same result when weights are nondegenerate. We have:

PROPOSITION 1. When stations are individually owned, truth-telling is a dominant strategy of the individual ownership weighted VCG mechanism.

The reader should observe at this point that the individual ownership weighted VCG mechanism is almost, but not quite, a collapsed version of the Deferred Acceptance auction. The difference is that the Deferred Acceptance auction implicitly utilizes a greedy algorithm, while the individual ownership weighted VCG mechanism utilizes full optimization. Thus, the Deferred Acceptance auction is an obviously strategy proof mechanism, while the individual ownership weighted VCG mechanism is not. At the same time, if bidders play their dominant strategies, then the individual ownership weighted VCG mechanism will generate greater social surplus than the Deferred Acceptance auction utilizing the same weights, because it fully optimizes the weighted objective.

3.3 Joint ownership bidder-weighted VCG mechanism

The joint ownership bidder-weighted VCG mechanism is defined similarly to the standard VCG mechanism, except for: (1) the use of weights; and (2) disallowing package bidding (i.e., a bidder who owns multiple stations is obliged to submit a separate bid for each station). Note that in the Single Tower and Two Towers models specified in Section 1, multi-station owners have additive preferences over stations, and so the latter limitation does not preclude them from truthful bidding. The joint ownership bidder-weighted VCG mechanism is developed as follows.

Each station $j = 1, \ldots, J$ reports a value, $\hat{v}_j$, representing the minimum payment that the station would accept in order to relinquish its license. Let $x_j = 1$, if a station "wins" in the auction (i.e., if the station is paid to relinquish its license), and $x_j = 0$, otherwise. Let $x = (x_1, \ldots, x_J)$ denote the allocation vector. The feasible set, X, is the set of all allocations satisfying the feasibility constraint, i.e., all allocation vectors x such that the set of stations retaining their broadcast licenses can be repacked into the available channels.

Associated with each bidder $i = 1, \ldots, I$ is a bidder weight $\omega_i > 0$ and a set of stations S_i owned by the bidder. The weight of each station $j = 1, \ldots, J$ is given by the weight of the bidder who owns this station, i.e., $w_j = \omega_i$ for all $j \in S_i$. We let $\frac{1}{w}\hat{v}$ denote the weighted vector of value reports, i.e., $\frac{1}{w}\hat{v} = \left(\frac{1}{w_1}\hat{v}_1, \ldots, \frac{1}{w_J}\hat{v}_J\right)$. The auctioneer determines the outcome by computing a weighted value-minimizing allocation:

$$x^* \in \arg\min\left\{x \cdot \tfrac{1}{w}\hat{v} \mid x \in X\right\} \text{ and } \alpha = \min\left\{x \cdot \tfrac{1}{w}\hat{v} \mid x \in X\right\}. \tag{1.7}$$

Paralleling the development of the VCG mechanism, the auctioneer also minimizes value under the assumption that bidder i is absent from the auction (and all stations in S_i retain their broadcast licenses):

$$\alpha_i = \min\left\{x \cdot \tfrac{1}{w}\hat{v} \mid x \in X \text{ and } x_j = 0 \text{ for } \forall j \in S_i\right\}. \tag{1.8}$$

The *joint ownership bidder-weighted VCG mechanism* is the mechanism that establishes the allocation x^* and pays p_i to each bidder such that $x_j^* = 1$ for at least one station in S_i, where:

$$\frac{p_i}{\omega_i} = \alpha_i - \left(\alpha - \sum_{j \in S_i \text{ and } x_j^* = 1} \frac{\hat{v}_j}{w_j}\right). \tag{1.9}$$

With weights $\omega_i = 1$, for all $i = 1, \ldots, I$, the bidder-weighted VCG mechanism coincides with the standard VCG mechanism (except for package bidding)—and therefore it is a dominant strategy mechanism here. The usual VCG reasoning implies the same result when weights are nondegenerate. We have:

PROPOSITION 2. When stations are jointly owned, truth-telling is a dominant strategy of the joint ownership bidder-weighted VCG mechanism.

4. Equilibrium Analysis of Examples

When stations are individually owned or in a joint ownership bidder-weighted VCG mechanism, the equilibrium analysis is straightforward, as truth-telling is a dominant strategy. However, for other scenarios or mechanisms, the equilibrium analysis can be quite formidable and there will necessarily be an absence of fully general results. Still, the consideration of several instructive cases can be quite illuminating.

Throughout this section, we will focus on a particular special case of the models of Section 1—the case where the number n_H of full-power stations is 2, the number n_L of low-power stations is 4, and k = 2, i.e., there are four available channels in the Single Tower model or two available channels in each city of the Two Towers model. In addition, we will assume that the distribution F from which the value of a full-power station is drawn is the uniform distribution on $[0, \overline{v}]$, where $\overline{v} > 1$, and that the distribution G from which the value of a low-power station is drawn is the uniform distribution on [0,1]. For notational convenience, we reorder stations such that $v_1 \geq v_2$ and $v_3 \geq v_4 \geq v_5 \geq v_6$.

4.1 Bidder 1 owns two full-power and bidder 2 owns four low-power stations, each with independent values

Consider a scenario in which bidder 1 is a station group that owns both full-power stations, while bidder 2 is a station group that owns all four low-power stations. Furthermore, we assume that all values are drawn independently. In this scenario, in the Deferred Acceptance auction or the individual ownership weighted VCG mechanism, both bidders have strong incentives for supply reduction. In particular, the Deferred Acceptance auction has the equilibrium in which bidder 1 immediately exits on its more valuable station 1 and bidder 2 immediately exits on its more valuable stations 3 and 4. As a result, the feasibility constraint is satisfied at $t = 0$, and each remaining station j $(j = 2, 5, 6)$ relinquish their broadcast licenses in exchange for a price of $p_j(0)$. We have:

Proposition 3. Suppose that $\overline{p} = \max\left\{1, \frac{\overline{v}}{w_H}\right\}$. Then, the Deferred Acceptance auction has the following equilibrium for any $w_H > 0$:

$$\begin{aligned} &\text{Bidder 1 exits at } (p_1, p_2) = (w_H \overline{p},\ v_2) \text{ and} \\ &\text{Bidder 2 exits at } (p_3, p_4, p_5, p_6) = \left(\overline{p},\ \overline{p},\ \frac{v_5 + v_6}{2},\ v_6\right), \end{aligned} \tag{1.10}$$

where p_j denotes a drop-out price for station j.

By contrast, in the joint ownership bidder-weighted VCG mechanism, truth-telling is a dominant strategy (see Proposition 2, above).

The expected value of the relinquished stations (i.e., the expected social cost of clearing) in this equilibrium of the Deferred Acceptance auction is $\frac{3}{5} + \frac{\overline{v}}{3}$; and the auctioneer's expected clearing cost is $(2 + w_H)\overline{p}$.

Figures 1 and 2 illustrate the comparison of the auctioneer's expected clearing costs and efficiency between the Deferred Acceptance auction (labelled DA multi-station) and the joint ownership bidder-weighted VCG mechanism (labelled VCG multi-station) for a variety of weights. In Figure 1, $\overline{v} = 2$, and so the expected value of a full-power station is two times the expected value of a low-power station (the same ratio as the extra space that a full-power station occupies). In Figure 2, $\overline{v} = 4$, and so the expected value of a full-power station is four times the expected value of a low-power station (so a social planner would tend to find it optimal to clear low-power stations). For illustrative purposes, we also plot the same metrics for the Deferred Acceptance auction and the weighted VCG mechanism (labelled as DA single-station and VCG single-station) in the environment where each station is owned by a different bidder (and so truthful bidding is a weakly dominant strategy).

Figure 1. Independent Values Model with $\overline{v} = 2$

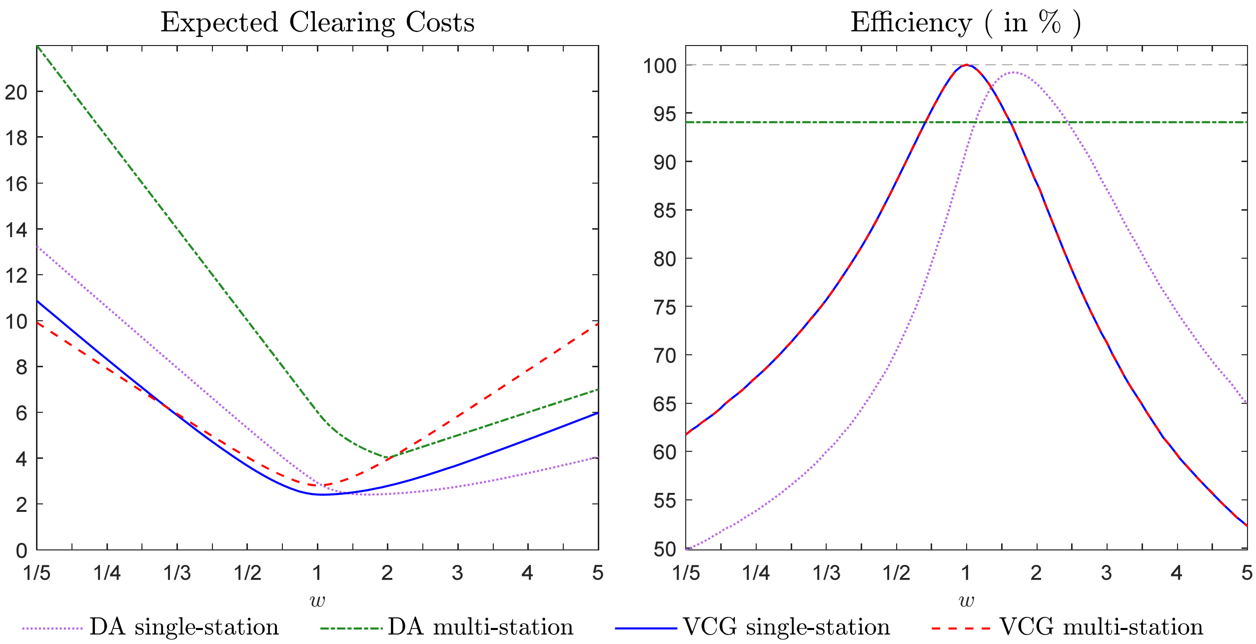
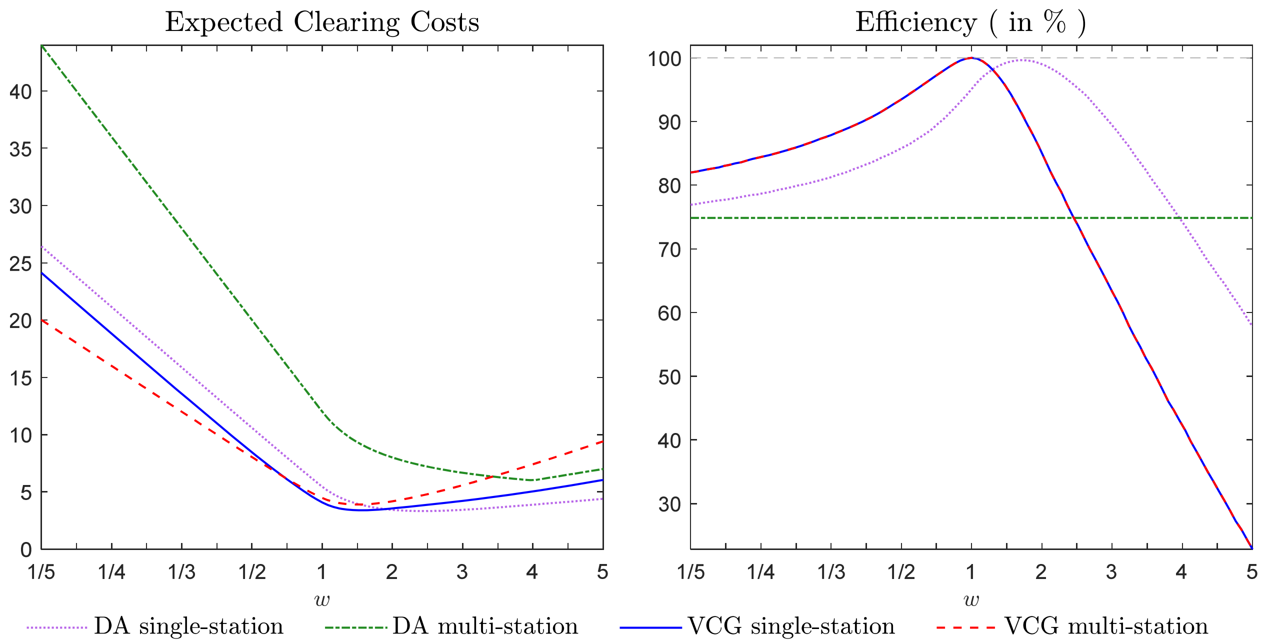


Figure 2. Independent Values Model with $\overline{v}$ = 4



Observe that the Deferred Acceptance auction's expected clearing cost is minimized at w_H = 2 when $\overline{v} = 2$, and at w_H = 4 when $\overline{v} = 4$. In each case, the cost-minimizing weight for the joint ownership bidder-weighted VCG mechanism is lower: w_H = 1 when $\overline{v} = 2$, and w_H = 1.5306 when $\overline{v} = 4$. The more striking conclusion is that the expected clearing cost, evaluated at the optimal weight, can be radically lower for the joint ownership bidder-weighted VCG mechanism than for the Deferred Acceptance auction, while also generating higher efficiency.

4.2 Bidder 1 owns two full-power and bidder 2 owns four low-power stations, each with perfectly-correlated values

In this section, we continue to consider the model from the previous section. However, we assume perfect correlation instead of independence: both full-power stations have the same values, $v_1 = v_2 \equiv v_H$, and the four low-power stations have the same values, $v_3 = v_4 = v_5 = v_6 \equiv v_L$. The Deferred Acceptance auction has the same equilibrium with supply reduction as the model with independence. The expected value of the relinquished stations in this equilibrium is $1 + \frac{1}{2}\overline{v}$; and the auctioneer's expected clearing cost is still $(2 + w_H)\overline{p}$.

Figure 3.Perfect Correlation Model with $\overline{v} = 2$

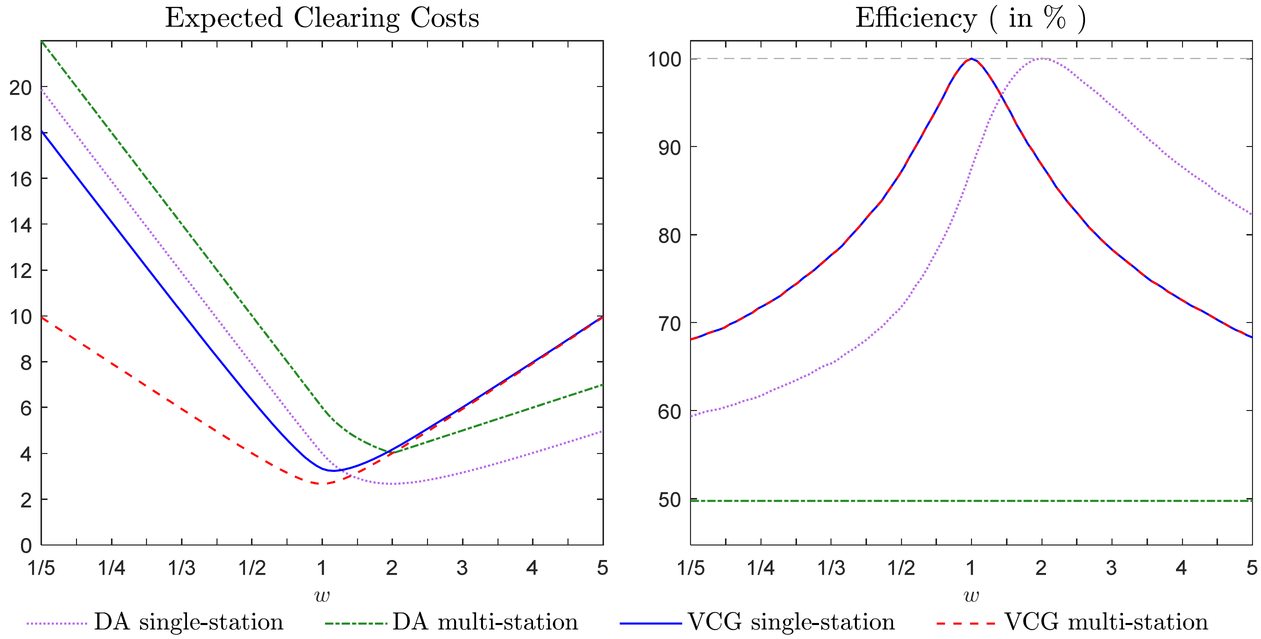
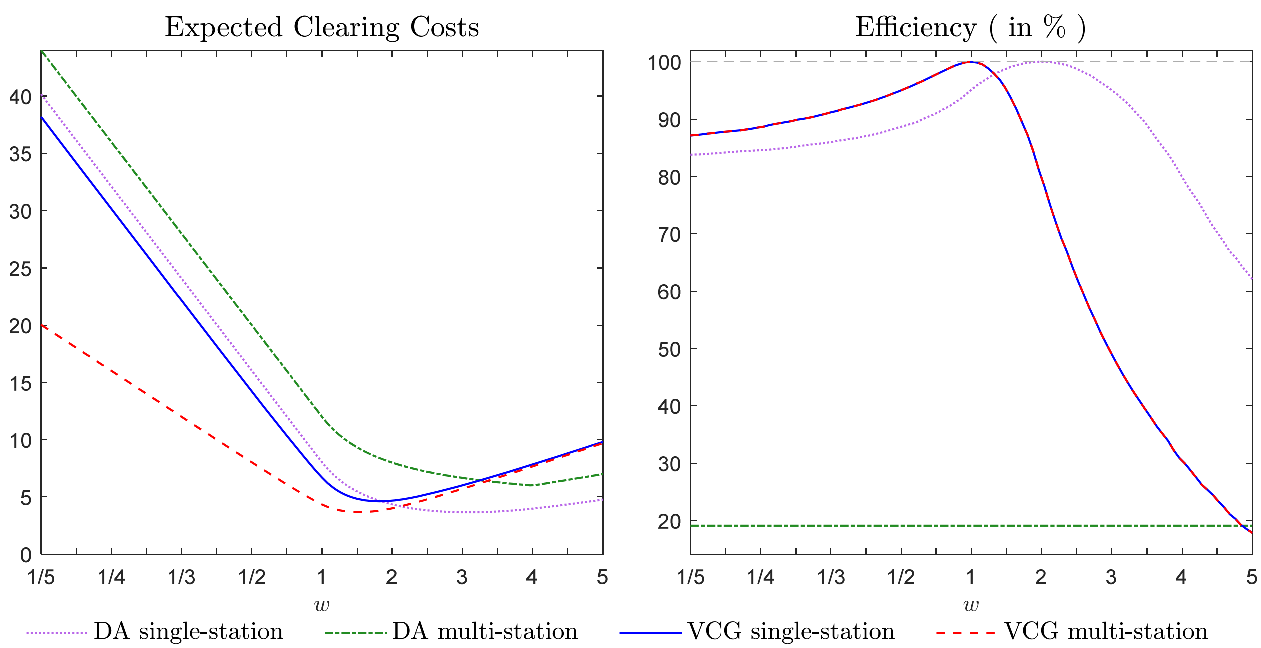


Figure 4. Perfect Correlation Model with $\overline{v} = 4$



4.3 Model with Correlation of One-Half ($\gamma = 0.5$)

Figure 5.Half Correlation Model with $\overline{v} = 2$

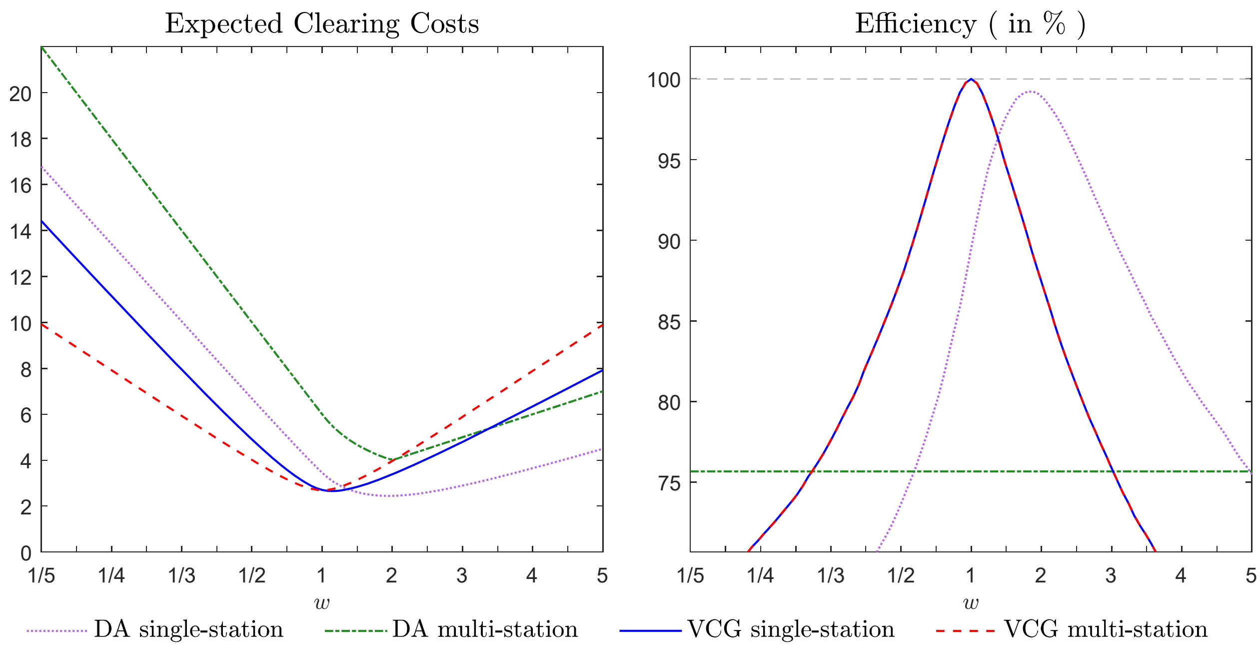
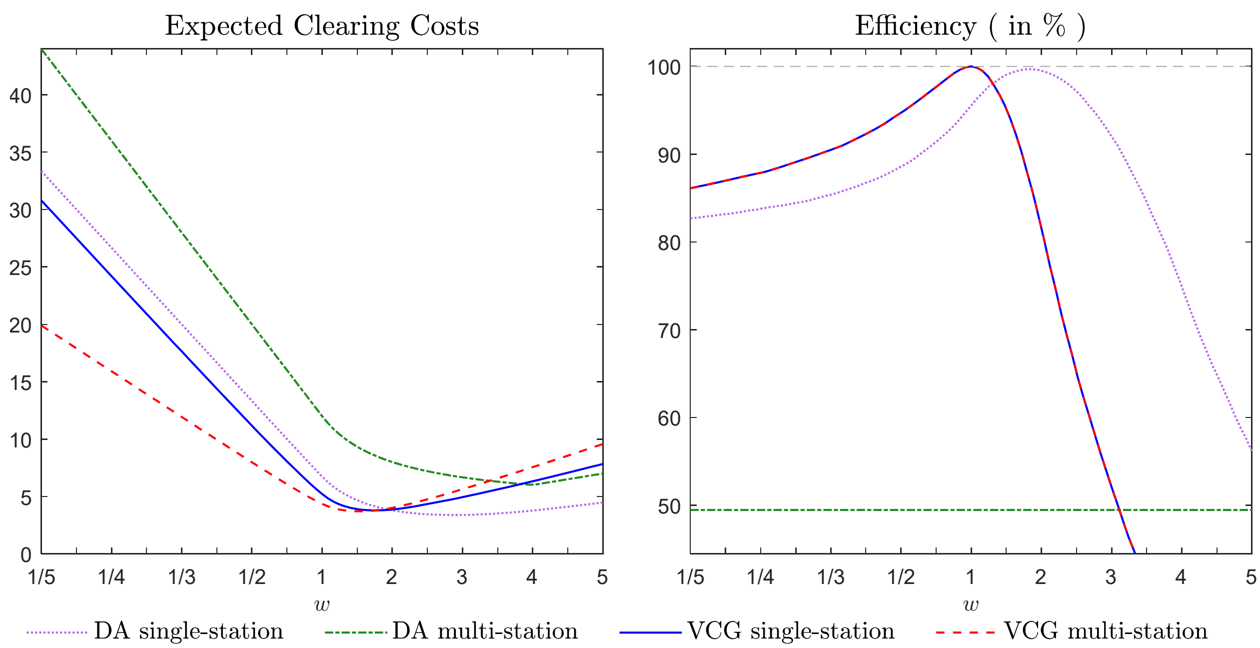


Figure 6. Half Correlation Model with $\overline{v} = 4$



5. Empirical Evidence

The possibility of supply reduction in the Broadcast Incentive Auction has been observed in previous studies. Doraszelski et al. (2017) documented the significant purchases of licenses by private equity firms in the run-up to the auction and showed that multi-license holders would be able to earn large rents from a supply reduction strategy. Ausubel et al. (2017) provided evidence of potential supply reduction in the reverse auction based on the auction results (i.e., the winning stations and the payments they received) that the FCC published at the conclusion of the auction, in April 2017.

In this section, we provide the first analysis that has been done of the full bidding data from the reverse auction (i.e., the losing stations and the prices at which they exited). The bidding data reveals much stronger evidence of supply reduction than any previous analyses and, in our view, makes the most compelling empirical case for supply or demand reduction seen anywhere in the literature to date.

5.1 Drop-out prices matched with resale prices

The starkest evidence of supply reduction is provided by OTA Broadcasting, LLC (OTA), a private equity firm founded by Michael Dell's MSD Capital. OTA acquired 23 TV stations before the auction, including 11 stations in the Pittsburgh market. OTA entered all 23 of these stations into the auction, but sold only ten of them in the auction. Of its 11 Pittsburgh stations, OTA only sold five in the auction.

The usual challenge in detecting supply (or demand) reduction in empirical data is that the bidder's true cost (or value) for the marginal items is not directly observable, making it difficult to put forth an unassailable argument that the bidder reduced its supply (or demand) below the truthful level. However, in the current instance, OTA sold almost all of its remaining stations shortly after the conclusion of the auction. Moreover, the sales agreements were filed with the FCC and therefore have become observable to researchers. The disclosed sales prices, along with the bidding data, provide strong evidence that OTA engaged in supply reduction.

Table 3. Pittsburgh stations sold by OTA Broadcasting in November 2017

<table>
<tr><th>DMA</th><th>Station</th><th>Purchase Price</th><th>Drop-Out Price</th><th>Resale Price</th></tr>
<tr><td>Pittsburgh, PA</td><td>WWKH-CD</td><td rowspan="6">In May 2013, OTA purchased these six stations along with five other Pittsburgh stations[8]</td><td>$76,594,362</td><td rowspan="5">In November 2017, OTA resold these five stations as a group for $275,000</td></tr>
<tr><td>Pittsburgh, PA</td><td>WKHU-CD</td><td>$37,567,171</td></tr>
<tr><td>Pittsburgh, PA</td><td>WWLM-CD</td><td>$88,361,791</td></tr>
<tr><td>Pittsburgh, PA</td><td>WMVH-CD</td><td>$33,016,048</td></tr>
<tr><td>Pittsburgh, PA</td><td>WJMB-CD</td><td>$28,456,574</td></tr>
<tr><td>Pittsburgh, PA</td><td>WJPW-CD</td><td>$8,767,575</td><td>In October 2017, this license appears to have been allowed to cancel</td></tr>
<tr><td></td><td>Total</td><td>$8,625,000</td><td>$272,763,521</td><td>$275,000</td></tr>
</table>

[8] This was the purchase price for the 11 Pittsburgh stations, including a $1,375,000 increment if the FCC ruled that WEPA-CD was eligible to be bid in the BIA. WEPA-CD is one of the stations that OTA relinquished in the auction.

Table 3 summarizes the ultimate disposition of OTA's six Pittsburgh stations that were not relinquished in the auction. The sum of the prices at which OTA dropped these six Pittsburgh stations out of the auction was $272 million. If OTA had been bidding truthfully, its valuation for these six stations would be close to $272 million. However, shortly after the auction, OTA sold five of those stations for a total of only $275 *thousand*—about 1/1,000 of its drop-out prices[9]—and appears to have allowed the license of the sixth station to cancel as valueless. This is clear and convincing evidence that OTA's bids were not truthful and strongly suggests that OTA reduced its supply early in the auction in order to increase the payment it would receive for its remaining Pittsburgh stations.[10] As such, Table 3 may provide the most compelling empirical evidence of supply (or demand) reduction in the literature to date.

Further indication of supply reduction is provided by the fact that OTA bid to drop out of the auction for exactly one Pittsburgh station in each round, for rounds 2, 3 and 4 of the auction. It seems extraordinarily unlikely that these dropout bids would be connected to OTA's valuations for the stations. More likely, this was an attempt to freeze the other stations that OTA owned in the Pittsburgh market. OTA did not succeed in freezing its other stations in the first few rounds of the auction. It then stopped exiting its stations until round 22. In rounds 22, 23 and 32, OTA bid to drop out for three more of its Pittsburgh stations.

Table 4. Seattle stations sold by OTA Broadcasting in October 2017

DMA	Station	Purchase Price	Drop-out Price	Resale Price
Seattle-Tacoma, WA	KFFV	$3,450,000	$23,717,150	$13,100,000
Seattle-Tacoma, WA	KVOS-TV	$2,900,000	$9,459,692	

Table 4 above provides information about two other stations that OTA sold in October 2017, suggesting that OTA also employed a supply reduction strategy in the Seattle market. It is particularly telling that the bid to drop out for KFFV in Seattle occurred in the first round of the auction, when the prices were still very high.

5.2 Drop-outs in early rounds of the auction

Bids to drop out in the early rounds of the auction are likely to be related to supply reduction in cases where the bidder also had other stations in the auction with which the station dropping out interfered. In this section we show that, as would be expected if bidders were employing supply reduction strategies, the stations that were part of a station group and interfered with other stations in the group were more likely than stations not satisfying this condition to drop out of the auction early.

[9] We should be cautious here and acknowledge that $275,000 may somewhat understate OTA's true value, as OTA may have engaged in a rush sale to liquidate these assets before the end of the tax year. However, OTA's tax benefit would appear to be bounded by the capital gains tax rate (23.8%) of 2017 multiplied by OTA's purchase price for the five stations, making it exceedingly difficult to impute a true value exceeding one or two million dollars.

[10] OTA received a combined payment of $73.9 million for relinquishing five stations in the Pittsburgh market in the Broadcast Incentive Auction.

We say that a station *s* has *in-group constraints* if there is another station *t* that entered the auction such that (a) stations *s* and *t* have co-channel interference on channel 20,[11] and (b) stations *s* and *t* were entered by the same bidder. For criterion (b), we consider each of the two datasets described below:

Initial ownership data. This is the dataset that was provided by the FCC, where each station is associated with a bidder name and an FCC Registration Number (FRN). Two stations are treated as owned by the same bidder if and only if the two stations were associated with the same FRN in this dataset.

Merged ownership data. Sometimes the same company applied to participate in the auction with different bidder names and different FRNs, for some or all of its stations. Based on publicly filed ownership information, sometimes requiring our judgment, we identified such instances and constructed the merged ownership data. In such instances, two stations are treated as owned by the same company even though they were associated with different FRNs in the initial ownership data.

The following table shows the number of UHF stations that dropped out early along with how many of those stations had in-group constraints using each dataset.

Table 5. Proportions of stations that dropped out early

Round N	**Number of UHF stations that dropped out by Round N (across all stages)**				
	Of all 930 UHF stations in auction	Of the 251 UHF stations with in-group constraints using the initial ownership data		Of the 366 UHF stations with in-group constraints using the merged ownership data	
	Number of stations	Number of stations	p-value of 2-sample test for equality of proportions	Number of stations	p-value of 2-sample test for equality of proportions
1	24	16	9.145e-06***	17	0.00138***
2	34	20	2.042e-05***	23	0.00058***
5	49	27	5.244e-06***	30	0.00128***
10	75	38	1.453e-06***	44	0.00036***

Observe that the proportion of stations with in-group constraints that dropped out early is higher than the proportion of stations without in-group constraints that dropped out early. To verify this statistically, we use 2-sample tests for equality of proportions. For each of the rounds shown in the table above and for each dataset, the 2-sample test for equality of proportions yields a p-value that is less than 0.05 (and, in fact, well below 0.01), leading us to reject the hypothesis of equal proportions.

We are looking at dropouts in early rounds, since our theoretical model predicts dropouts at the very beginning. If one examines dropouts over the entire auction (N = 52), the test yields a p-value of 0.6051

[11] The results are similar if a different UHF channel is chosen for this definition, because if two stations have an interference constraint on one UHF channel, they typically also have interference constraints on other UHF channels.

when using the initial ownership data and a p-value of 0.3304 when using the merged ownership data (i.e., $p > 0.05$), which means that we cannot reject the hypothesis of equal proportions.[12]

In the remainder of this section we provide examples of bids to drop out early that may be related to supply reduction.

Entravision Holdings participated in the auction with 23 stations. In the first round of the auction, it bid to drop out for eight of those stations. Each of those eight stations interfered with at least one other Entravision station that remained in the auction after the first round, suggesting that Entravision employed a supply reduction strategy.

NRJ TV is a private equity firm that acquired TV licenses before the Broadcast Incentive Auction. NRJ TV participated in the auction with 14 stations, including three stations in the Los Angeles market, two stations in the San Francisco market, and two stations in the Philadelphia market. In the second round of the auction, even though the prices were still very high, NRJ TV bid to drop out for a station in the Los Angeles area and a station in the San Francisco area, presumably trying to freeze other stations that NRJ TV owed in California. Indeed, one of its other Los Angeles stations and its San Diego station became frozen after the round.

LocusPoint, another private equity firm participated in the auction with nine stations. Two of those stations were in Florida. In the first round of the auction, LocusPoint bid to drop out for one of those stations, presumably attempting to freeze its other Florida station.

It is not only the large bidders or the private equity firms that appear to have employed supply reduction strategies in the auction. For example, Central Michigan University participated in the auction with five stations (all in the state of Michigan), and bid to drop out for four of those stations in the first round of the auction, presumably as an attempt to freeze its fifth station. As another example, Spanish Broadcasting System Holding Company participated in the auction with three stations (all in Puerto Rico), and bid to drop out for two of those stations in the first round of the auction, presumably as an attempt to freeze its third station.

Supply reduction was not limited to the early rounds of the auction, though in the early rounds of the auction a supply reduction strategy has the potential of being more profitable. For instance, Venture Technologies may have employed a supply reduction strategy, when in round 40 of stage 4, it bid to drop out one of its Los Angeles stations (KHTV-CD) at around $50 million. This appears to have immediately frozen its other Los Angeles station, KSFV-CD, at $63.96 million.

6. Conclusion

[To be added]

[12] Specifically, 774 out of all 930 UHF stations dropped out during the auction, 198 out of the 251 stations with in-group constraints when using the initial ownership data dropped out during the auction, and 287 out of the 366 stations with in-group constraints when using the merged ownership data dropped out during the auction.

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