Efficiency or Competition? A Structural Econometric Analysis of Canada's AWS Auction and the Set-Aside Provision*

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June 27, 2014

Abstract

In 2008 Industry Canada auctioned 105MHz of spectrum to a group of bidders that included incumbents and potential new entrants into the Canadian mobile phone market, raising $4.25 billion. In an effort to promote new entry, 40MHz of spectrum was set-aside for new entrants. In order to estimate the implicit cost of the set-aside provision, we estimate the parameters of the bidders' profit function via a maximum match estimator based on the notion of pairwise stability in matches. We find that all telecommunications firms valued both geographic complementarities across auction licenses as well as absolute spectrum. Under a reasonable counterfactual scenario our results indicate that the set-aside led to a total profit loss of approximately 10%.

Keywords: Spectrum, Set-Aside, Structural Matching, Pairwise Stability, Maximum Score.

1 Introduction

Auctions are ubiquitous as an interface for procurement of goods and services as well as allocation of scarce resources; when coupled with the rapid growth of internet and online auction houses, auctions are an attractive mechanism at the disposal of businesses and governments alike. Regardless of the seller (government or corporation) or the auction venue (an auction house or the internet), appropriate auction design is of utmost importance. For example, India's recent experience highlights the significance of developing transparent methods for allocating spectrum. Their 3G auction concluded in May 2010 and generated $14.6 billion in revenue. This amount far exceeded expectations, and led to a re-evaluation of the previous 2G auction. Indeed, a recent report suggests that the previous allocation mechanism — which, following a surprise, last-day, rule change, essentially

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became first-come first-served — for the 2G licenses may have cost the Indian government \$40 billion in lost revenue and has led to a political scandal.[1] We feel safe, therefore, in our assertion that the proper design and implementation of these auctions is of paramount importance for both economic and political reasons.

The auction designer often faces challenges and has many conflicting goals. For example, should a government body seek to maximize revenue, auction efficiency (in the sense that the highest value bidders win), or should they maximize another objective function such as social welfare, where the value to consumers is considered as well?[2] Similarly, should a business allow a single firm to become its sole supplier or should it seek two or more suppliers, even at the cost of paying more and increasing the complexity of the supply chain? It is, therefore, crucial to be able to determine whether the indirect benefits of auction rules to, say, ensure downstream competition or a diversified supply chain out-weigh the direct costs due to restricting what bidders may win. Only then can one make an informed decision about the ideal auction design in the face of conflicting goals.

Two common tools that have been used by both governments and businesses are bid-caps and set-asides. A bid-cap limits the amount that any single bidder can win, thereby ensuring at least two winners, which, depending on the context, ensures downstream competition or multiple suppliers. For example, in the rough diamond industry BHP Billiton (now the Dominion Diamond Corporation) limits the amount that any one company can win in certain product categories in order to ensure a competitive downstream market (Cramton, Dinkin, and Wilson, 2013). A set-aside limits the goods that certain bidders can place bids on. For example, in spectrum auctions, set-asides have been used to promote entry into the market for wireless services, by reserving certain blocks of radio spectrum for small bidders and/or new entrants.[3] Perhaps counterintuitively, set-asides also have the potential to increase revenue (see, e.g. Ayres and Cramton (1996), Rothkopf, Harstad, and Fu (2003) and Milgrom (2004), among others), though to the extent that lower value bidders win, such a policy leads to lower auction efficiency in the traditional sense.

In 2007, when Industry Canada was tasked with designing an auction to allocate Advanced Wireless Spectrum (AWS), the familiar trade-off between revenue maximization and promoting downstream competition was particularly germane. A government report noted that the relatively concentrated Canadian wireless market may be an important reason why there are "higher [consumer] prices, less innovation, lower uptake and lower rates of usage" (Industry Canada, 2007, p. 3) than in other markets. In the end, the Canadian government instituted policies that they hoped would lead to increased downstream competition with more choice and lower prices for consumers. Specifically, the 2008 AWS Auction included a set-aside provision, carving out 40MHz of spectrum

[1] See the articles, "Telecom Scandal Plunges India Into Political Crisis," *The New York Times*, December 14, 2010, A1. and "Bids Total \$11 Billion for Wireless Spectrum in India," *The New York Times*, May 20, 2010, B13.

[2] Recent work by Hazlett and Munoz (2009, p. 425) argue persuasively for making as much spectrum available as possible, even at the cost of sacrificing revenue, stating that, "Today, U.S. wireless phone market data yield an annual consumer surplus estimate of at least \$150 billion. The total revenue obtained from selling all wireless licenses (not just for mobile telephony) is just \$53 billion. Given that the latter is a present value and the former an annual flow, these data suggest that the ratio ([consumer surplus] to [producer surplus]) is much above an order of magnitude."

[3] They have also been used in timber auctions (Athey, Coey, and Levin, 2012), among others.

for new entrants. They also imposed rules limiting the ability of the eventual winners of this set-aside spectrum from later re-selling it to the big 3 incumbents for five years. Our goal in this paper is to evaluate the Canadian government's policy decision in light of the above discussion and to seek to quantify the tradeoff between efficiency and the promotion of downstream competition. This is relevant as there is ongoing debate surrounding what measures, if any, are required or justifiable to ensure lasting competition. However, this exercise is valuable beyond simply the realm of evaluating one specific policy in the market for spectrum. As we have noted, the concerns held by the Canadian government are often shared in other markets and by both public and private entities.

The present work is noteworthy in several aspects. First, this is (to the authors' knowledge) the first academic study of the Canadian AWS spectrum auction. Second, because of the structure of the AWS auction, we must consider multiple blocks of spectrum simultaneously when analyzing the auction, which is a departure from previous studies (Hazlett and Munoz, 2009, Fox and Bajari, 2013). Thus, we can consider both vertical (i.e., the amount of spectrum won in any single geographic area) and horizontal (the geographic footprint) differentiation of the spectrum. Finally, outside of Athey, Coey, and Levin (2012), this is the only paper (to our knowledge) that studies empirically the impact of an auction set-aside, and the first to do so for a spectrum auction.

Greater understanding of the impacts of set-asides is imperative given the myriad theoretical predictions of a set-aside. By reducing competition on set-aside licenses, it could lead to lower bids placed on these licenses. On the other hand, downstream competition may be enhanced because the set-aside makes it easier for fringe companies to win spectrum. Another indirect consequence of the set-aside may be to impede firms' ability to fully exploit geographic complementarities by reducing the number of available licenses that can be bid on. Given the opposing costs and benefits of the set-aside, it is instructive to determine the impact of alternative auction formats to determine how outcomes might have looked in the absence of the set-aside.

In our structural econometric analysis we compute the value of the collection of licenses (called packages) obtained by the winning bidders. We can then compute the change in auction efficiency moving from the observed allocation to several alternative scenarios which may have arisen under different policy choices by the Canadian government. Our estimates show a maximal possible efficiency gain of about 30% (or $1.28 billion). However, this scenario assumes that a single bidder wins *all* of the spectrum — an unlikely scenario. Two potentially more relevant scenarios are (i) there was no set-aside and (ii) all of the spectrum was set-aside for new entrants. In the former case, we calculate an efficiency gain on the order of 6.7 to 11.7%. The upper bound of this range translates into approximately $497 million. In the latter case, our results indicate a change in efficiency ranging from -5.7% to 2.7%.

We next turn to a more speculative discussion of whether social welfare may increase as a result of increased competition due to the set-aside. Because of changes in the wireless market, such as the rapid growth of smartphones, occurring simultaneously with the entry of new providers after the AWS auction, it is exceedingly difficult to quantify the change in social welfare. We can say that the 1 million or so customers of the new entrants are better off as a result of the set-aside. Moreover, the data that we do have suggest that it is at least *possible* that prices to all consumers went down as a result of the set-aside. However, we end this discussion by casting doubt on the sustainability of increased competition due to the financial difficulties of two of the main new entrants.

The remainder of the paper proceeds as follows. Section 2 highlights several connections with the present work and the broader literature on auction analysis. Section 3 describes the Canadian AWS auction in detail. Section 4 discusses the pairwise matching estimator used to estimate the structural profit function. Section 5 details our construction of geographic complementarities as well as other components of firms' structural profit function. Section 6 presents our econometric results and analysis of alternative allocations designed to gauge the effectiveness of the AWS auction. In Section 7, we discuss whether the auction may have increased social welfare, and if the increased competition is sustainable. Section 8 concludes.

2 Related Literature

Our research is related to the auction literature appearing in the operations management, telecommunications, applied industrial organization and structural econometrics fields. Below, we briefly highlight the literature in operations management as well as the literature in economics/econometrics that is germane to the topics discussed here.

2.1 Operations Management Literature

Within operations management there exists an extensive body of work on auctions. A great deal of this research has focused on procurement (or reverse) auctions in business-to-business (B2B) settings.[4] There are many differences between spectrum auctions and B2B procurement auctions. First, Elmaghraby (2007), notes that in B2B settings, price is often just one of many dimensions which determine the winner; beyond this, the auctioneer need not be committed to actually transacting with the lowest bidder in so-called buyer determined auctions. Second, in what Rothkopf and Whinston (2007) call "business rules", buyers might have strategic reasons to limit the amount that can be won by any supplier in order to foster long-run competition by suppliers and protect their supply chains from shocks. Therefore, like our spectrum auction, these non-price characteristics may create an efficiency loss in the auction in the service of some other goal. The tools in our paper could help quantify these efficiency losses in other contexts.

There are also several theoretical papers which look at how sellers can use auctions (perhaps in combination with list prices) as a revenue/inventory management tool.[5] As a practical application some diamond miners now use auctions as a revenue management tool to sell some of all of their supply (e.g., Rio Tinto Diamonds and BHP Billiton). Cramton, Dinkin, and Wilson (2013) discuss

[4]See, e.g., Jap (2002, 2003), Elmaghraby (2004, 2007), Cachon and Zhang (2006), Gallien and Gupta (2007), Rothkopf and Whinston (2007) and Kostamis, Beil, and Duenyas (2009).

[5]For revenue management, see Caldentey and Vulcano (2007), van Ryzin, Garrett and Vulcano (2004) and Pinker, Seidmann, and Vakrat (2010), while for inventory see Huh and Janakiraman (2008) and Chen, Roundy, Zhang, and Janakiraman (2005).

BHP Billiton's use of auctions — its relation to our paper is their use of bid caps to ensure long-run downstream competition from their buyers.

There are few empirical studies of procurement auctions beyond those focusing on internet businesses (such as eBay). Two recent exceptions are Olivares, Weintraub, Epstein, and Yung (2012) and Kim, Olivares, and Weintraub (Forthcoming), which look at a combinatorial auction in Chile used by the government to procure school meals. Olivares, Weintraub, Epstein, and Yung (2012) take a reduced form approach in seeking to estimate the participating firms' cost structures and their bidding strategies. They show that package bidding allows bidders to express cost savings due to economies of scale/density. However, they also show that package bids are used strategically to discount some package bids that are not due to cost reductions from winning the package. Like us, they are also interested in studying the effects of mechanisms to increase downstream competition — in their case, market share restrictions and the use of sequential auctions; in our case, the set-aside of 40MHz of spectrum for new entrants. Somewhat in contrast to our results, they show that the restrictions are effective at promoting long-run competition without substantially increasing the procurement costs to the government. In a subsequent paper, using the same Chilean data, Kim, Olivares, and Weintraub (Forthcoming) take a structural approach in order to determine whether the positive effect of package bidding (by allowing bidders to express cost synergies) outweighs the negative strategic effect in which certain packages are discounted while inflating single bids even when cost synergies are absent. Their results show that the allocative efficiency of the auction is approximately 98% and that bidders' margins are approximately 5%. They attribute the high efficiency and "reasonable" margins to the highly competitive nature of the auctions, which limits the market power of firms and their ability to profit from strategic bidding. Although the AWS auction we consider was not a combinatorial auction, we are also interested in estimating complementarities/synergies and adopt a structural approach in order to estimate firm's profit functions. Our approach constructs packages of licenses and then considers pairwise trades of licenses in order to identify the main parameters of our model — in particular the influence of geographic complementarities on bidder valuations.[6]

2.2 Economics and Econometrics Literature

Within the economics literature there exists a large body of work focusing on auction design. However, combining generic auction design with the specific issues of spectrum management and sale there is a much smaller window. Ayres and Cramton (1996) argue that set-asides and other mechanisms designed to give preferential treatment to certain groups are valuable tools that governments/sellers may wish to use in order to raise revenues. In contrast, Hazlett and Munoz's (2009) analysis makes clear that one must be aware of the potential for unintended consequences from such policies. For example, they argue that the FCC C Block Auction, which restricted participation to small bidders and gave favorable payment terms to winners, but later saw several prominent

[6]The underlying assumption is that, at the final allocation, it should not be possible for two bidders to exchange licenses in a way that increases the sum of profits.

bankruptcies, was actually worse for consumers than if the auction had been open to all bidders.

Outside the realm of spectrum auctions, Athey, Coey, and Levin (2012) have analyzed the results of several hundred timber auctions conducted by the U.S. Forest Service. Their results suggest that set-asides reduce auction efficiency and government revenues significantly, and they argue that properly designed subsidies would increase government revenue, improve auction efficiency and raise profits of small bidders, all at a relatively small cost to the profits of large bidders.

Given the structural nature of our econometric approach we also note that even though a burgeoning literature on the structural estimation of auctions exists,[7] very is concerned with spectrum auctions. An exception is the elegant study of Fox and Bajari (2013) who investigated the FCC C Block Auction conducted between 1995 and 1996. Their findings suggest that geographic complementarities across licenses were a significant component of a telecommunications firm's decision to bid, making up a significant portion of a package's value to any given firm. At the same time, they argue that an auction consisting of 4 large regions would have roughly increased allocative efficiency by as much as 66% relative to the actual C block setup, and that it would have significantly raised the proportion of the US population that was won by high-value bidders. While our study is closest to Fox and Bajari (2013) several differences arise. First, they focus on a single block of spectrum, whereas our AWS auction is comprised of eight blocks. This is an important difference that allows for different ways to think about complementarities across licenses. Further, the FCC C block auction divided the continental United States into 480 distinct geographic regions, essentially allowing telecommunications firms to determine where geographic complementarities existed. The Canadian AWS auction, at its finest partition, divided Canada into 59 distinct geographic regions. Given that the two countries are of roughly the same size, the extent of complementarities is expected to be different and so rote transfer of their results are not likely to be representative. Lastly, and most importantly, the FCC C block auction did not have a set-aside in place. Thus, our analysis of the impact of this policy tool cannot be guided from the work of Fox and Bajari (2013).

3 The Auction, Bidders, and Bidder Behavior

Industry Canada's auction for Advanced Wireless Spectrum (AWS) took place between May 27, 2008 and July 21, 2008. In total 90MHz of AWS spectrum in the 2GHz range, as well as 10MHz of the PCS Expansion Band and the 5MHz band in the 1670-1675 MHz range were up for auction. 27 bidders submitted qualifying applications but only 21 bidders actively participated in the auction.

3.1 Details on Spectrum Blocks

The 90 MHz of AWS spectrum was divided into 6 blocks (A – F), while the PCS Expansion band was the G block and the 1670-1675 MHz range was labeled the I block.[8] In addition, each of the

[7] See the special issues on the "Econometrics of Auctions" (Dubois, Ivaldi, and Magnac, 2008) and "Auctions and Games" (Kumbhakar and Sickles, 2012).

[8] Each block represents a particular tranche of radio frequency that the winner is given exclusive access to. For example, the A block gave the winner the right to transmit wireless communications over the ranges of spectrum

license blocks was partitioned into either 14 tier 2 licenses (basically larger economic regions) or 59 tier 3 licenses (smaller metropolitan regions). As we noted, one of the important features of this auction was that 40MHz of AWS spectrum (the B, C and D blocks) was set aside exclusively for those firms labeled as new entrants, while the rest of the spectrum was open to all bidders.[9] Table 1 outlines the important details of the auction.

Table 1: Auction Details

Block	A	B	C	D	E	F	G	I
MHz	20	20	10	10	10	20	10	5
Tier	3	2	2	3	3	3	2	2
Spectrum	Open	S/A	S/A	S/A	Open	Open	Open	Open
# Licenses	59	14	14	59	59	59	14	14
# Sold	59	14	14	59	59	59	12	6
Price/(MHz×population)	1.67	1.21	1.35	1.27	1.72	1.91	0.26	0.11

"Open" means that all bidders were eligible to bid on the spectrum, while "S/A" means that this spectrum was set-aside for new entrants (with 3 incumbents forbidden from bidding).

As a prelude to the notation that we will use, Tier 2 blocks, $j \in \{B, C, G, I\}$, are denoted $\{201j, 202j, \ldots, 214j\}$, while Tier 3 blocks, $k \in \{A, D, E, F\}$, are denoted, $\{301k, 302k, \ldots, 359k\}$. Therefore, it should be understood that the first digit represents the tier structure, the second and third digits represent the geographical area, while the letter denotes the frequency block. Note that the Tier 3 licenses can be viewed as a refinement of the partition of Tier 2 licenses. Thus, for example, license 203C and the set of licenses 305D, 306D and 307D are equivalent in the sense that they would each give the winner 10MHz of spectrum covering the province of New Brunswick. However, because bidders were required to bid on licenses individually (i.e., package bids, as in a combinatorial auction, were not permitted), the tier 3 licenses may create an *exposure problem* for a bidder who only wants to win a collection of licenses which covers all of New Brunswick. Therefore, tier 3 licenses could conceivably sell for less than the equivalent geographical package of tier 2 licenses.

While lower frequencies have better transmission properties, the six AWS spectrum blocks were generally thought to be near perfect substitutes for each other (e.g., the A and F blocks were essentially equivalent); however, there may have been cost savings from winning spectrum in different licenses areas in the same block. Note also that because of their different technical characteristics, the G and I blocks were generally viewed as less desirable and were not expected to generate as much revenue as the AWS spectrum. Indeed, much of this spectrum went unsold, and that which was sold was done so at a steep discount to the AWS spectrum. Concerning the G Block, it was only the recent decision by US Carrier Sprint-Nextel to deploy its 4G LTE network on

1710-1720MHz and 2110-2120MHz. Except for the I block, the spectrum was paired into an upper and lower band of spectrum used for uplinks from mobile devices to base stations and downlinks from base stations to mobile devices.

[9]New entrants were defined as those bidders who had less than 10% of the national market by revenue. In effect, this rule excluded the three large national wireless operators (Bell, Telus and Rogers) while at the same time allowed two much smaller regional incumbents, SaskTel and MTS, to bid in the set-aside.

this frequency band that led to increased handset support capable of operating on this spectrum.[10]

3.2 The Auction Format

The auction design was a *simultaneous multiple round auction* (SMRA). Before the auction began, each bidder submitted a deposit, which gave bidders eligibility points in proportion to the size of their deposit. Each license had a number of eligibility points associated with it. In each round, bidders would place bids on a subset of the available licenses at the going price up to their maximum eligibility, subject to the rules of the set-aside. An activity rule forced bidders to place bids on a certain percentage of their total eligibility, or else they would lose eligibility in subsequent rounds.[11] Bidding was "yes/no", which means that bidders stated whether or not they were willing to pay the going price for any particular license. At the conclusion of each round, if more than one bidder placed a going price bid on a license, one bidder was randomly selected as the *standing high bidder*. For those licenses in which there was excess demand, the price of the license would increment up by a pre-specified percentage. In the next round, bidders would then express their willingness to pay the new going price for each license, with the auction ending if no new bids were placed.[12]

The auction lasted 331 rounds, spread out over 39 bidding days, with 10,037 bids being placed. In total, 282 of the 292 licenses (including all of the AWS spectrum) were sold, with 15 different bidders winning licenses. The auction generated approximately \$4.25 billion in sales of licenses and withdrawal penalties — an amount that nearly tripled initial expectations of \$1.5 billion.[13] In Figure 1(a) we plot the number of bids submitted in each round (not including round 1). As can be seen, bidding remained active until about round 100, with 60 or more new bids being received each round. After that, bidding gradually slowed down and by round 200, there were generally 10 or fewer new bids placed each round. In Figure 1(b) we plot the auction revenue in each round by the standing high bidders and the total bidder exposure, which captures the total value of all standing high bids plus new bids placed in each round. As is often the case, revenue quickly increased in early rounds, but by round 150 it was over 97% of the final amount. Interestingly, bidder exposure reached a local peak in round 16 at \$4.19 billion — 98.5% of the final auction revenue more than 300 rounds later. The fact that exposure peaked so early suggests, according to Bulow, Levin, and Milgrom (2009), that many of the bidders faced binding budget constraints.

Finally, Table 1 also shows the final normalized selling prices in each block (i.e., the price per person per MHz of spectrum or $/(MHz × pop) for short). Observe that the average price per MHz×pop of set-aside spectrum was approximately \$1.28, while for open spectrum, the average

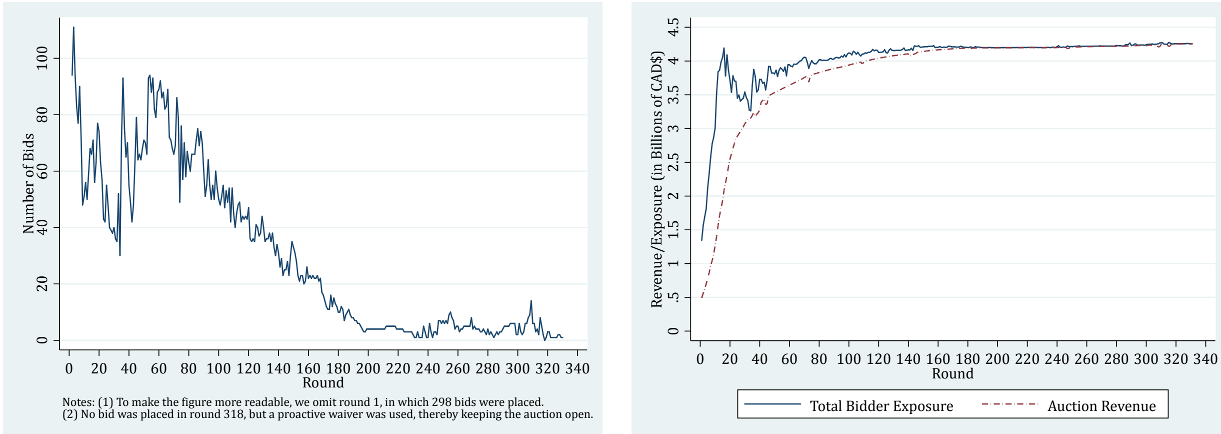
[10] See `http://www.publicmobile.ca/pmconsumer/pressReleases/index?idx=2`.

[11] In early rounds, bidders were only required to bid on licenses totaling 75% of their eligibility to preserve eligibility. In later rounds, they had to bid on 100% of their eligibility.

[12] The standing high bidder was not obligated to bid the new price for the license, but could do so if it so chose. Such a bid is referred to as a *jump bid*. Jump bids may be used strategically for a variety of reasons. We discuss them in Appendix A. The standing high bidder could also withdraw its bid, subject to potential withdrawal penalties if the final selling price was lower, with the license then reverting back to the previous standing high bidder.

[13] See the article, "Options abound as auction kicks off," Financial Post, 27 May 2008, in which it was reported that "[t]he auction is expected to raise about \$1.5 billion for the federal government."

Figure 1: Number of Bids, Auction Revenue and Bidder Exposure (By Round)



(a) Number of Bids

(b) Auction Revenue & Bidder Exposure

price was approximately \$1.77 per MHz×pop. Thus, entrants paid only about 73 cents on the dollar for an equivalent amount of open spectrum, and suggests that the efficiency loss due to the set-aside may be non-negligible.

3.3 The Bidders

Twenty-one bidders actively participated in the auction. The three nationwide incumbents were Rogers, Bell and Telus, and all of them offer mobile services nationwide. Additionally, Bell and Telus evolved out of the traditional telephone monopolies and provide fixed and wireless phone services, internet and cable TV services. Except for wireless services, Telus primarily operates in Western Canada and Bell in Eastern Canada. In addition to its wireless services, Rogers also provides internet and cable TV services, primarily in Ontario. Both Bell and Rogers own other media outlets such as TV and radio stations and newspapers. Before the AWS auction, Rogers had approximately 85MHz of spectrum nationwide, while Telus had between 30 and 45MHz nationwide, with more spectrum in Western Canada. Finally, with the exception of Saskatchewan and Manitoba, Bell had between 25 and 55MHz of spectrum across Canada, with more spectrum in Eastern Canada.

The entrants were more diverse. Among the most serious bidders, SaskTel and MTS were existing providers of fixed-line and wireless telephone, and internet services in Saskatchewan and Manitoba, respectively. Shaw, Vidéotron and Eastlink offered cable TV and internet services in Western Canada, Québec and Atlantic Canada, respectively.[14] Vidéotron, through its parent company, also had several media outlets within Québec. There were two large, “pure play” wireless entrants: Mobilicity and Wind Mobile. Wind Mobile’s goal was to obtain a national footprint; to do so, it received substantial foreign investment, leading to intense litigation surrounding whether

[14] We refer to the entrants by their brand, rather than their business name for the auction. Thus we refer to Globalive as Wind Mobile, DAVE as Mobilicity, Quebecor as Vidéotron and Bragg as Eastlink.

it exceeded foreign ownership restrictions.[15] Mobilicity focused on the major cities. In addition to these entrants, there were several other smaller entrants which focused on obtaining spectrum in very specific regions. For example, Public Mobile only bid on spectrum in the G Block.

4 Econometric Framework

4.1 Pairwise Stability in Matches

Our estimation approach is based on the assumption that, at the final allocation, the auction satisfies a property known as *pairwise stability in matches*. The basic intuition is that two bidders i and j should not be able to exchange licenses $\ell_i \in J_i$ and $\ell_j \in J_j$ (where J_m is the set of licenses won by bidder m) and have the total surplus increase. More formally, an allocation of spectrum satisfies pairwise stability in matches if for all bidders i and j and for all licenses $\ell_i \in J_i$ and $\ell_j \in J_j$,

$$\pi_i(J_i) + \pi_j(J_j) \geq \pi_i(\{J_i \setminus \ell_i\} \cup \{\ell_j\}) + \pi_j(\{J_j \setminus \ell_j\} \cup \{\ell_i\}),$$

where $\pi_m(J_m)$ denotes valuation of bidder m for the set of licenses, J_m. That is, the joint surplus is higher at the actual final auction outcome than when considering any pairwise trade of licenses between any two bidders. The notation $\{J_i \backslash \ell_i\} \cup \{\ell_j\}$ implies that the package of licenses obtained by bidder i has one license replaced by one of bidder j's winning licenses. Observe that prices paid for licenses do not enter the above equation. This is because the prices paid for the packages J_i and J_j would appear on both sides of the inequality and, therefore, cancel.

To the extent that pairwise stability holds, a matching estimator may be used to estimate the parameters of the structural profit function, where the objective function is the fraction of pairwise license transfers that do not raise joint surplus. Thus, the validity of our empirical strategy rests on whether pairwise stability in matches can be expected to hold. Although this is a difficult question to answer for general auctions with complementarities, Fox and Bajari (2013) show that pairwise stability in matches holds in Brusco and Lopomo's (2002) model of simultaneous ascending auctions with complementarities, despite the presence of collusive equilibria. Thus, pairwise stability in matches is, at least partially, robust to collusion. Fox and Bajari (2013) also show that, in some auctions, pairwise stability in matches holds even if, in equilibrium, bidders engage in a strategic demand reduction to win fewer licenses but at lower prices.[16] Beyond verifying that pairwise stability in matches holds in a number of theoretical settings, Fox and Bajari (2013) also analyzed data from Banks, Olson, Porter, Rassenti, and Smith's (2003) experimental auctions designed to simulate the FCC spectrum auction. They showed that over 90% of winning packages satisfy pairwise stability, and in over half of the auctions, pairwise stability is satisfied 100% of the time.

Thus, the theoretical and experimental evidence make a compelling case that pairwise stability in matches can be expected to hold in practice. However, there is one important caveat with respect

[15] At present complete foreign ownership of a wireless operator is permitted, provided its market share is small.

[16] This is important because, as shown in an online appendix, there is some evidence that bidders attempted to send tacit signals of strength/intentions via the use of jump bids and/or tit-for-tat bidding strategies.

to the AWS auction: Because of the set-aside, incumbents were unable to bid on set-aside spectrum. Therefore, pairwise stability in matches need not be satisfied for pairs of licenses, one coming from an incumbent, and the other from an entrant in the set-aside. Indeed, since such a trade would run afoul of the auction rules, we will not consider them in our empirical analysis below.

Remark 1. *One could consider a stronger condition known as pairwise stability in prices and matches, which is satisfied if for all bidders i and j and for all licenses $\ell_i \in J_i$ and $\ell_j \in J_j$,*

$$\pi_i(J_i) - p_{\ell_i} \geq \pi_i(\{J_i \setminus \ell_i\} \cup \{\ell_j\}) - p_{\ell_j}.$$

However, we focus on pairwise stability in matches only because it imposes fewer restrictions and is compatible with equilibrium bidding strategies. Moreover, as Fox and Bajari (2013) point out, pairwise stability in prices and matches is considerably less likely to hold in the experimental auctions of Banks, Olson, Porter, Rassenti, and Smith (2003). Finally, results with prices lead to estimates of complementarities that are "absurdly high" Fox and Bajari (2013, p. 132).

4.2 The Maximum Match Estimator of Fox (2009)

We now describe the structural econometric estimator we will use to estimate bidders' structural profit function. Let $a = 1, \ldots, \mathcal{B}$ index the bidders. Fox (2009) proposes a maximum match (or rank) estimator (Manski (1975), Han (1987)) which is designed to minimize the number of times two different bidders would want to trade a single license from the package of licenses with each other. If the bidders had truly constructed their optimal packages (under pairwise stability) then no trades would be agreed upon. The objective function for this problem is

$$Q(\beta) = \frac{2}{\mathcal{B}(\mathcal{B}-1)} \sum_{a=1}^{\mathcal{B}-1} \sum_{b=a+1}^{\mathcal{B}} \sum_{i=1}^{|J_a|} \sum_{j=1}^{|J_b|} 1\left\{\mathcal{I}_{ij}(\beta) \geq 0\right\}, \tag{1}$$

where $\mathcal{I}_{ij}(\beta)$ measures the relative benefit of exchanging licenses ℓ_i and ℓ_j across competing packages and β is the vector of parameters to estimate. The indicator function, $1\{\mathcal{A}\}$, takes the value 1 when the event $\mathcal{A}$ is true and is 0 when the event $\mathcal{A}$ is false. The relative benefits of swapping licenses across packages are defined as

$$\mathcal{I}_{ij}(\beta) = \bar{m}_a(J_a;\beta) + \bar{m}_b(J_b;\beta) - \bar{m}_a((J_a \backslash \{\ell_i\}) \cup \{\ell_j\};\beta) - \bar{m}_b((J_b \backslash \{\ell_j\}) \cup \{\ell_i\};\beta), \tag{2}$$

where $\ell_i \in J_a$ and $\ell_j \in J_b$. $\bar{m}_a(J_a;\beta)$ represent the structural profits accrued by bidder a that is observable to the econometrician. Once $\bar{m}_a(J_a;\beta)$ is parametrically specified, $\widehat{\beta} = \max_\beta Q(\beta)$, which can be obtained using non-gradient optimization algorithms.

This estimator is econometrically meaningful in our setting where pairwise stability is assumed to hold. In essence pairwise stability generates a set of rank order conditions which generate an equilibrium sorting pattern in the data which can then be exploited to obtain coefficient estimates for the structural profit function. For the AWS auction we believe that pairwise stability is satisfied, except for trades involving an incumbent and an entrant holding set-aside spectrum.

The maximum match estimator of Fox (2009) can be placed in a broader class of maximum rank estimators recently studied by Subbotin (2007). While his work focuses on conditions for establishing consistency of the bootstrap, Subbotin (2007) obtains $\sqrt{n}$-asymptotic normality for a wide array of maximum rank estimators. To obtain confidence intervals for our estimates of β one could resort to asymptotic distributional results. However, the limiting distribution of maximum rank estimators, while normal, have variance-covariance matrices that are difficult to recover. Therefore resampling schemes provide an alternative avenue to obtain valid confidence intervals and test statistics. As such two main alternatives exist. One could deploy a subsampling mechanism, as in Politis and Romano (1994), or a bootstrap approach following Subbotin (2007). We outline the subsampling approach here since the bootstrap approach poses several conceptual difficulties regarding the pairwise exchange of licenses.

The subsampling algorithm of Politis and Romano (1994) (advocated by Fox (2009)) is simple to implement; the main complication is how to take the subsamples. In a standard regression setting the subsampling mechanism of Politis and Romano (1994) would fix a subsample size and then draw repeated samples without replacement of that size, reestimate the model and then construct confidence intervals. However, in the current setting our observations are not *iid* draws from a cross sectional distribution. Rather, these observations are linked via the exchange of licenses across two packages. The approach for subsampling in this context is to take subsamples of the *packages* as opposed to the actual matches. For example, in our setting we have 15 total packages, so a subsample of 6 packages would produce a total number of observations to estimate the parameters of the matching function equal to the total number of pairwise license exchanges across those 6 packages, $\binom{15}{6} = 5005$. We set the number of packages to sample at 8 since $\binom{15}{8}$ results in the largest number of different combinations (6435) across smaller numbers of packages.

To detail the construction of the subsampled confidence intervals we use the following notation. Let the total number of matches be denoted as n and the size of a given subsample be n_s. We let $\hat{\beta}_{MM}$ denote our original maximum match estimate and $\hat{\beta}_{SS}$ be our subsampled maximum match estimate. The subsampling process to construct a $1-\alpha$ confidence interval is as follows:

1. Sample without replacement from the packages.

2. Estimate β for the structural profit function using the subsampled packages.

3. Construct $TE = n_s^{1/2}(\hat{\beta}_{SS} - \hat{\beta}_{MM})$.

4. Repeat steps 1-3 $\mathcal{C}$ times.

5. Find the $\alpha/2$ and $1-\alpha/2$ quantiles of TE. Denote these values as $TE_{[\alpha/2]}$ and $TE_{[1-\alpha/2]}$, respectively.

6. The $1-\alpha$ confidence interval of $\hat{\beta}_{MM}$ is $n^{-1/2}[\hat{\beta}_{MM} - TE_{[\alpha/2]}, \hat{\beta}_{MM} - TE_{[1-\alpha/2]}]$.

5 Construction of the Structural Profit Function

The structural profit function used by Fox and Bajari (2013) takes the following parametric form:

$$m_a(J_a;\beta) = \pm 1 \cdot e_a \cdot \left(\sum_{j \in J_a} pop_j\right) + \beta' x_{J_a} + \sum_{j \in J_a} (\xi_j + \varepsilon_{a,j}) \tag{3}$$

where e_a represents the initial eligibility of bidder a (in terms of what fraction of the population the bidder is eligible to win), $\sum_{j \in J_a} pop_j$ is the total population covered by package J_a and x_{J_a} contains information about certain characteristics of a winning package, J_a. ξ_j is a license-specific fixed effect and $\varepsilon_{a,j}$ represents bidder a's independent private value for license j. Note that ξ_j, when included in the match function in (2) above, would appear on both sides of the inequality; hence, it does not need to be estimated. The interaction between initial eligibility and $\sum_{j \in J_a} pop_j$ captures the observed finding that bidders with more initial eligibility won more licenses. In this section, we define the variables which might appear in x_J.

5.1 Construction of the Profit Function Covariates

For the characteristics of a winning package we first focus on geographic complementarities. As mentioned, geographic complementarities may be expected to determine a large component of the value of a package of licenses (this was one of the key findings in Fox and Bajari (2013)). While the specific setup of the FCC C block Auction (480 distinct license areas) and the Canadian AWS auction (at most 59 distinct license areas) partition their countries differently, we believe enough spatial heterogeneity exists that bidders can determine where their specific complementarities may exist. We present heuristic evidence for the presence of geographic complementarities.

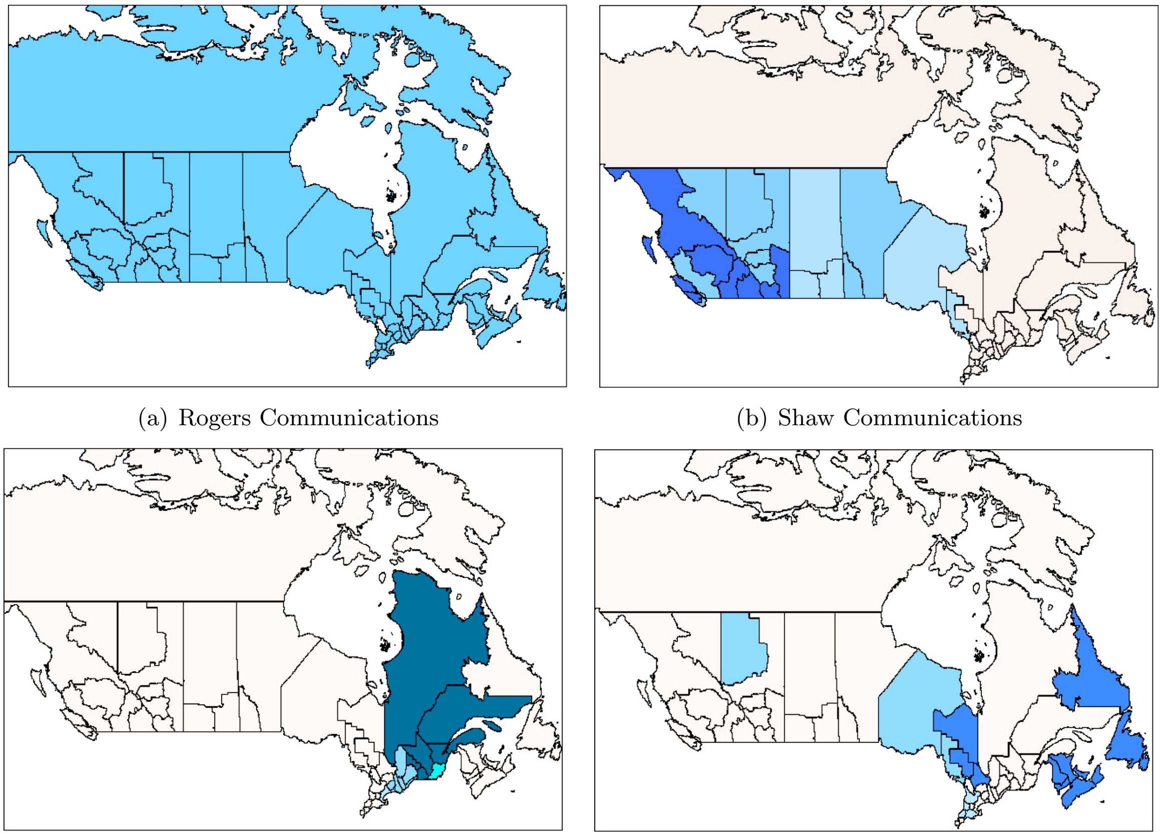
5.1.1 Existence of Geographic Complementarities

To discern the existence of geographic complementarities, we first focus attention on the geographic footprints of bidders. First, the two winningest bidders in terms of dollars (Rogers and Telus) both won licenses covering all of Canada, while the third and fourth winningest bidders (Bell and Wind Mobile) tried, unsuccessfully, to obtain a national footprint. For these four bidders, we expect there to be strong geographic complementarities.[17] Second, geographic complementarities are likely present for the other bidders, though their magnitude may be limited for other reasons. As noted, many of the entrants were existing cable TV (Shaw, Vidéotron and Eastlink) or regional telecom companies (SaskTel and MTS). These bidders already had brand recognition in their respective markets, though the cable companies did not have any pre-existing spectrum. Therefore, rather than seeking a national footprint, they may have been more focused on consolidating their position in the geographical area where they were already active by being able to provide complementary

[17] Complementarities can be seen as similar in spirit to the economies of density studied by Olivares, Weintraub, Epstein, and Yung (2012) in their analysis of combinatorial auctions in Chile.

services (e.g., by adding wireless to their bundle of services).

Figure 2: Geographic Footprints of Select Winning Bidders (Spectrum From AWS Auction Only)



(a) Rogers Communications

(b) Shaw Communications

(c) Vidéotron

(d) Eastlink Wireless

The geographic footprints of four winners are given in Figure 2. The darker the shading, the more frequency that was won in a given area. Those areas in white indicate that the bidder did not win any spectrum in that region. As can be seen, with some exceptions, Shaw, Vidéotron and Eastlink did appear focused primarily on winning spectrum in their existing markets of Western Canada, Quebec and Atlantic Canada, respectively. Finally, in Appendix B we conduct a regression analysis in the spirit of Ausubel, Cramton, McAfee, and McMillan (1997) and find further evidence for the likely presence of geographic complementarities. Specifically, the price paid for license i is statistically significantly higher if the second-highest bidder for license i won an adjacent license. This demonstrates that bidders valued swaths of spectrum as opposed to individual licenses.

5.1.2 Constructing Geographic Complementarities

Let J denote a package of licenses and L the collection of all geographic blocks in the AWS auction.[18] Fox and Bajari (2013) measure geographic complementarities as:

[18] In Fox and Bajari (2013) this is equivalent to the number of available licenses. With multiple blocks covering the same geographic region, L defines the number of distinct geographic areas for which a bidder could obtain spectrum.

$$geo_J = \sum_{i \in J} pop_i \left(\frac{\sum_{j \in J, j \neq i} \frac{pop_i pop_j}{dist_{ij}^{\delta}}}{\sum_{j \in L, j \neq i} \frac{pop_i pop_j}{dist_{ij}^{\delta}}} \right), \tag{4}$$

where pop_i (pop_j) is the fraction of the population that reside in the region covered by license i (j), $dist_{ij}$ is the distance (in kilometers) between licenses i and j and $\delta = 4$. An appealing feature of this measure of complementarities is that it is non-decreasing in the number of licenses won. Also, $0 < geo_J \leq 1$, with $geo_J = 1$ indicating that the bidder won at least one license in every region.

However, unlike the FCC C-Block auction which contained only one license in each region, the AWS auction had 6 AWS spectrum blocks and 2 other blocks of spectrum in each geographic area. Moreover, licenses differed in terms of the number of MHz. Therefore, an important question is whether geographic complementarities interact with the amount of spectrum won. We argue that there is good reason to expect that they may, in fact, interact. Bidders may be concerned about being able to offer a consistent level of service across their geographic footprint. However, if they win 30MHz of spectrum in one area but only 10MHz of spectrum in another area, then their ability to offer identical service in both areas is limited because of insufficient capacity in the latter area.[19] This may reduce the effect of complementarities. Second, we see in Table 8 of Appendix B that the *amount* of adjacent spectrum won by the second highest bidder of a license had a positive effect on the price paid by the eventual winner of that license. To capture this interaction between geographic complementarities and the amount of spectrum won, we consider an alternative measure:

$$geo_J^M = \sum_{i \in J} pop_i MHz_i \left(\frac{\sum_{j \in J, j \neq i} \frac{pop_i pop_j}{dist_{ij}^{\delta}}}{\sum_{j \in L, j \neq i} \frac{pop_i pop_j}{dist_{ij}^{\delta}}} \right). \tag{5}$$

But for the inclusion of MHz in the outer summation, everything else is identical to (4).[20] From now on we will refer to (5) as *spectrum-weighted geographic complementarities* and (4) as *unweighted geographic complementarities.*

Recall also that some of the blocks were tier 2 licenses (larger economic regions) while others were at the tier 3 level (smaller metro regions). This raises some technical issues as to how geographic complementarities are computed. For example, suppose that bidder i has the package $J_i = \{211C\}$, while bidder j has the package $J_j = \{341D, 342D, 343D\}$. In this example, both packages correspond to 10MHz of spectrum covering Saskatchewan, but the package J_i does so with a single tier 2 license, while the package J_j does so with three tier 3 licenses. Intuitively, bidders i and j have exactly the same geographic footprint, which means that the measure of geographic complementarities should also be the same. To do this, our calculation of geographic complemen-

[19]This argument may be one of the underlying motivations for the network sharing agreement between Bell and Telus. Telus (Bell) has relatively more spectrum in Western (Eastern) Canada. However, when combined via the sharing agreement, both firms' spectrum profiles are more balanced across Canada.

[20]In our empirical work, we experimented with non-linear versions of (5), such as having MHz enter as a quadratic or square root. In all such cases, the fit was worse than the linear-in-MHz specification that we have adopted; nor were there any qualitative differences in our findings.

tarities is done at the Tier 3 level. That is, we break down Tier 2 licenses into their constituent Tier 3 parts and then proceed with the appropriate computation.

5.1.3 Absolute Spectrum

Independently of geographic complementarities, the amount of spectrum won is also likely to enter into the structural profit function since more spectrum allows firms to offer more services or to provide the same service at a lower total cost (Church and Wilkins, 2013). Therefore, we include a measure of population-weighted average spectrum across the 59 Tier 3 license regions. That is,

$$spec_J = \sum_{i=1}^{59} pop_i MHz^2_{J,i}. \tag{6}$$

where $MHz_{J,i}$ is the amount of spectrum that package J contains in Tier 3 region i. We take MHz^2 to capture economies of scale with respect to having more spectrum in a given area.[21]

5.1.4 Spectrum Concentration

Finally, the multiplicity of licenses means that the number of eventual competitors in the market for wireless services is endogenous. Indeed, the value of a license in any given geographic area may depend (likely negatively) on the number of other bidders who win licenses in that same area. To create a proxy for the competition within a given geographic area we turn to the common Herfindahl index. Let $s_{j,K}$ denote the share of total available spectrum won by bidder j in region K. The Herfindahl index for region K is $H_K = \sum_{\ell \in w_K} s^2_{\ell,K}$, where w_K represents the set of bidders who won at least one license in region K. Our measure of competition for bidder j winning the set of licenses, J, is then the population-weighted concentration of spectrum won by bidders *other than* bidder j. That is,

$$comp^H_J = \sum_{i \in J} pop_i (H_i - s^2_{j,i}). \tag{7}$$

Remark 2. *By including competition into our model, we are implicitly assuming that there may be allocative externalities in bidder valuations. For a single object, Jehiel, Moldovanu, and Stacchetti (1996, 1999) find conditions for which an optimal mechanism exists and propose implementations of the mechanism. In multiple-object auctions, the Vikrey-Clarke-Groves mechanism can implement the welfare maximizing outcome (Jehiel and Moldovanu, 2005), but this will generally not be optimal for the seller. Perry and Reny (2005) propose an ascending auction which yields an efficient allocation in a multi-unit auction where bidders have interdependent valuations but the objects are homogeneous. Das Varma (2002) studies standard auctions of a single good with identity-dependent externalities and shows that open auctions generate greater revenue than sealed-bid auctions due to the option value of staying in the auction in order to learn information and avoid payoff reducing externalities. Goeree, Offerman, and Sloof (2013) study ascending clock auctions with multiple*

[21] Additionally, if MHz entered linearly, then it would largely be canceled out when we consider the effect on total surplus following a license swap.

homogenous goods but for which an entrant, if it wins, imposes an externality on incumbents. They show that there are a continuum of equilibria which contain both pre-emption and demand reduction. In experiments, they show that revenue and efficiency are lower than in sealed-bid auctions.

Little is known about the setting in the AWS auction in which there are multiple, heterogeneous goods for sale. However, we claim that the effect on pairwise stability of including competition should be relatively small. First, the externalities are largest between incumbents and entrants (where pairwise stability need not hold), but because of the set-aside, there was very little that the incumbents could do to pre-empt the entrants. Second, when trading two licenses of bidders i and j, the externality on other bidders is likely to be very small since such trades are unlikely to change the level of competition dramatically; instead such trades will, very often, simply change the identity of the competitors. Finally, for the two bidders involved in the pairwise trade, the effect on competition of the trade can, in some sense, be viewed in the same manner as a complementarity, and we have previously argued that pairwise stability in matches is a reasonable assumption.

In sum, the variables that we use to form various specifications of the structural profit function are: $x_J = \{geo_J, geo_J^M, spec_J, comp_J^H\}$.

6 Results

Before we present our empirical results, Table 2 provides a summary of bidder and winning package characteristics. Two bidders (13 and 15) won licenses covering Canada, though as the column geo^M indicates, bidder 13 won more total spectrum than bidder 15, reducing the extent of spectrum-weighted geographic complementarities for bidder 15. Also notice that the bidders captured a high percentage of geographic complementarities. Since some licenses went unsold, the maximum that geo^M (resp. geo) could take is 100.25 (resp. 7.006). As can be seen from the table, the actual allocation led to spectrum-weighted geographic complementarities of 94.37 (94.1% of the maximum), while unweighted geographic complementarities totaled 5.628 (80.3% of the maximum).

In terms of capturing spectrum-weighted geographic complementarities, the three incumbents were the most successful. At the same time, there were at least four entrants who captured fairly large geographic footprints. Table 2 also highlights some apparent differences in entrant-bidder strategies. For example, comparing bidders 3 and 4, it appears that the former attempted to win less spectrum but spread over a larger geographic footprint than the latter. One result of this is that bidder 3 faces a more competitive landscape than does bidder 4.

6.1 Maximum Match Estimation Results

Table 3 reports estimation results for a number of different specifications. Panel (a) restricts attention to unweighted geographic complementarities (*i.e.,* (4)), while Panel (b) provides results based on our spectrum-weighted measure of geographic complementarities (*i.e.,* (5)). As argued above, our preferred measure is spectrum-weighted geographic complementarities, but we include the unweighted version for comparison purposes. In brackets, below each estimate, we report the

Table 2: Summary of Bidder and Winning Package Characteristics

Bidder	Status	$elig \sum MHz \times pop$	geo	geo^M	$spec$	$comp^H$
1	Entrant	0.910	0.300	6.156	135.851	0.045
2	Entrant	0.163	0.033	1.168	45.652	0.004
3	Entrant	0.367	0.587	5.870	58.904	0.112
4	Entrant	1.485	0.301	10.642	431.820	0.060
5	Incumbent	0.937	0.866	12.783	214.707	0.153
6	Entrant	0.002	0.012	0.122	3.477	0.007
7	Entrant	0.063	0.096	2.596	101.467	0.021
8	Entrant	0.000	0.000	0.000	0.357	0.001
9	Entrant	0.267	0.438	4.828	67.106	0.080
10	Entrant	0.994	0.737	10.705	182.220	0.121
11	Entrant	0.037	0.228	2.278	22.951	0.037
12	Entrant	0.000	0.000	0.000	0.443	0.001
13	Incumbent	3.800	1.000	20.000	400.000	0.159
14	Entrant	0.013	0.028	1.113	52.026	0.003
15	Incumbent	1.413	1.000	16.114	283.410	0.171
Total	—	10.450	5.628	94.375	2000.39	0.974

95% confidence interval, based on the subsampling method outlined above. For now, we focus only on the sign and significance of the estimated coefficients. Given the differences in the underlying auction and the support of our variables, a direct comparison of the coefficients with Fox and Bajari (2013) (or even across specifications) is not possible. Later, when we consider alternative spectrum allocations, such comparisons are more transparent.

The first thing to notice is that, both measures of geographic complementarities are always significantly positive, though the estimates themselves vary substantially depending on the model under consideration. The fact that the coefficients on both *geo* and geo^M vary across specifications is likely due to the different scales of the other variables. Next, observe that the coefficient on competition is negative and significant in all four specifications. That is, the greater the downstream competition, the lower is the value to the bidders.

We next consider the effect of spectrum won by bidders. In particular, does the amount of spectrum won interact with geographic complementarities, does it have a separate effect, or possibly both? To gain insight, consider specifications (1a), (1b), (2a) and (2b). Specification (1a) does not control for the amount of spectrum won either directly or indirectly. Given that the fit is so much lower here than in any other case, it is clear that spectrum contains explanatory power beyond simple geographic complementarities. If we add the amount of spectrum directly by including *spec*, as in (2a), the fit improves by about 5 percentage points, and *spec* is found to be significant. On the other hand, if we control for the amount of spectrum indirectly via spectrum-weighted geographic complementarities, as in (1b), then geo^M is significant and the fit improves by 6.1 percentage points. Thus, the amount of spectrum won is important. Moreover, given the statistically significant

Table 3: Estimation Results for the Maximum Match Estimator

(a) Unweighted Geographic Complementarities

	(1a)	(2a)	(3a)	(4a)
$e\sum MHz\times$ pop	1	1	1	1
geo	14.37	5088.6	41.11	62.24
	$[5.985, 14.01]$	$[1072.9, 8152.1]$	$[27.65, 242.6]$	$[46.57, 216.9]$
$spec$		6.93		0.016
		$[1.024, 7.412]$		$[0.006, 0.047]$
$comp^H$			-180.7	-237.5
			$[-974.1, -133.8]$	$[-681.3, -171.3]$
Fit	0.8842	0.9308	0.9521	0.9575
p_{ss}	0.499	0.484	0.499	0.506

(b) Spectrum-weighted Geographic Complementarities

	(1b)	(2b)	(3b)	(4b)
$e\sum MHz\times$ pop	1	1	1	1
geo^M	2.47	55.92	19.18	16.69
	$[1.468, 4.971]$	$[14.87, 784.8]$	$[3.099, 55.64]$	$[7.172, 55.61]$
$spec$		0.19		0.028
		$[0.036, 0.625]$		$[0.008, 0.073]$
$comp^H$			-171.39	-104.5
			$[-126.8, -16.51]$	$[-227.6, -42.83]$
Fit	0.9449	0.9464	0.9459	0.9571
p_{ss}	0.511	0.514	0.509	0.491

95% subsampled confidence intervals (399 replications) in brackets below each estimated coefficient.
p_{ss} is the subsampled (399 replications) $p-$value of the Wald test for the null hypothesis that the coefficients are the same for entrants and incumbents.

coefficient on *spec* in (2b), the amount of spectrum won has a direct effect via *spec*, as well as an indirect effect via geo^M. Both the direct and indirect effects are positive, meaning that profits increase the more spectrum a bidder has.

These results affirm that the amount of spectrum a bidder wins has a strong affect on its profits. However, just by looking at the coefficients, it is difficult to get a sense of how big of an impact each of these variables has. For example, if a bidder wins more spectrum in a given region then, geo^M and *spec* will increase, while $comp^H$ will decrease, leading, in all cases, to an increase in profits. We would like to understand the relative contribution of each variable. When we consider alternative allocation scenarios, below, we will attempt to get at precisely this. Prior to this, we first investigate the sensitivity of our parameter estimates across the set-aside.

6.2 A Test of Parameter Stability

One hypothesis we find interesting is to determine if the coefficients of the structural profit function are constant across the set-aside and open auctions. In essence, did entrants value spectrum, beyond the effect of initial eligibility (which proxies for financial strength) differently than did incumbents? Our hypothesis is

$$H_0 : \beta_{S/A} = \beta_{Open}; \quad H_1 : \beta_{S/A} \neq \beta_{Open}. \tag{8}$$

A simple test statistic of our null hypothesis can be constructed using a Wald type statistic which only requires estimation of the unrestricted model. In this case we simply partition our data across auction form, estimate the coefficients of the structural profit function for each auction setup and use a subsampling inference procedure similar to that proposed by Delgado, Rodríguez-Poo, and Wolf (2001). We define our test statistic as $t_n = ||\beta_{S/A} - \beta_{Open}||$, where $||\cdot||$ is the L_2 norm. This will ensure that our statistic converges to 0 in probability under H_0 and to a positive constant under H_1. The final test statistic (given the subsampling) is $T_n = n^{1/2} t_n$.

Define $t_{n,SS,i}$ as the test statistic evaluated for a given subsample (as with our confidence intervals we subsample for eight firms). Then the sampling distribution of T_n is approximated by the subsampled distribution, for $\mathcal{D}$ subsamples

$$\hat{Q}(x) = \mathcal{D}^{-1} \sum_{i=1}^{\mathcal{D}} 1 \left\{ n_s^{1/2} t_{n,SS,i} \leq x \right\}. \tag{9}$$

The critical value for this distribution is obtained as the $1-\alpha$ quantile of $\hat{Q}(x)$, $\hat{q}(1-\alpha) = \inf \left\{ x : \hat{Q}(x) \geq \alpha \right\}$.

Under the assumption of pairwise stability *across all auctions* we would expect $\beta_{S/A} \equiv \beta_{Open}$. Given that both the open auction and the set aside contained both 20 and 10 MHz blocks, there is no evidence that better/worse blocks were set aside from the point of view of obtaining a far reaching geographic footprint. As we see from Table 3 we never reject the null hypothesis, using subsampled p-values, that the coefficients of the structural profit function are the same across auction type. This lends further evidence towards pairwise stability empirically.

6.3 An Analysis of the Set-Aside Mechanism

To properly evaluate the impact that the set-aside had on the allocation of spectrum we first need to understand how the AWS auction reallocated spectrum. We can then use these insights to construct alternative allocations that might serve as useful benchmarks when evaluating the set-aside.

6.3.1 Post Auction Spectrum Shares

In Table 4 we summarize the competitive landscape both before and after the AWS auction in the 6 largest markets. Specifically, the table reports the percentage of total spectrum held by each of the bidders. As can be seen, in these six markets (which collectively comprise over 50% of the Canadian population), the three national incumbents held virtually all of the spectrum, with Rogers claiming nearly half of the spectrum available. After the auction, the share held by the incumbents still remained over 80%. Rogers saw the largest decline in share of spectrum held, while Bell saw a more modest decline and Telus' share, outside of Toronto, fell only slightly. Except for Vidéotron in Montréal, none of the new entrants has more than 10% of the available spectrum, something which, as we will discuss in Section 7, hampers their ability to provide extensive data plans. The main conclusion is that in these 6 markets, consumers can now choose from 2 or 3 new providers.

Table 4: Spectrum Allocation Before and After AWS Auction (6 Largest Markets)

	Toronto		Montréal		Ottawa	
	Before	After	Before	After	Before	After
Company	% MHz	% MHz	% MHz	% MHz	% MHz	% MHz
Rogers	44.1%	35.2%	50.0%	38.9%	50.0%	38.9%
Bell	32.4%	27.8%	26.5%	20.4%	26.5%	20.4%
Telus	23.5%	18.5%	23.5%	22.2%	23.5%	22.2%
Wind Mobile	0.0%	7.4%	0.0%	0.0%	0.0%	3.7%
Vidéotron	0.0%	3.7%	0.0%	14.8%	0.0%	7.4%
Mobilicity	0.0%	3.7%	0.0%	0.0%	0.0%	3.7%
Other	0.0%	3.7%	0.0%	3.7%	0.0%	3.7%

	Vancouver		Edmonton		Calgary	
	Before	After	Before	After	Before	After
Company	% MHz	% MHz	% MHz	% MHz	% MHz	% MHz
Rogers	50.0%	38.9%	50.0%	38.9%	48.6%	38.2%
Bell	23.5%	18.5%	23.5%	18.5%	22.9%	18.2%
Telus	23.5%	22.2%	26.5%	24.1%	25.7%	23.6%
Wind Mobile	0.0%	3.7%	0.0%	3.7%	0.0%	3.6%
Mobilicity	0.0%	3.7%	0.0%	3.7%	0.0%	3.6%
Shaw	0.0%	7.4%	0.0%	7.4%	0.0%	7.3%
Other	2.9%	5.6%	0.0%	3.7%	2.9%	5.5%

Highlighted cells denote that the entrant has deployed the spectrum in that region.

The year 2013 was one in which many of the new entrants' financial difficulties became pronounced. Of the four entrants (Wind, Mobilicity, Public Mobile and Vidéotron) that have been operating since 2010, only Vidéotron appears to be financially stable. In Section 7 we will provide more discussion of the new entrants and whether they can bring lasting competition.

6.3.2 Alternative Spectrum Allocations

We consider four alternative spectrum allocation scenarios in the lack of a set-aside. First, we consider by what percentage the structural profit function (summed over all winning bidders; i.e., aggregate profits) would have changed if, given our estimated parameters, the bidder with the highest initial eligibility (*i.e.,* Rogers) won all of the licenses. This allocation is the one that maximizes $e\sum MHz \times pop$, geo^M and *spec*, while also leading to minimal competition.

Second, we consider by what percentage aggregate profits would have changed in the absence of a set-aside, where we assume that the spectrum would have been divided according to the pre-existing market shares of the three large incumbents and the two smaller regional providers, to the exclusion of all other entrants. This represents what we feel to be the most likely outcome in the absence of a set-aside.[22] Third, we consider the case in which all of the spectrum was set-aside for new entrants, with the additional spectrum being allocated according to the new entrants in proportion to their winning shares in the actual auction. We feel that these two scenarios represent plausible outcomes in the two extreme cases of either no set-aside or a complete set-aside. The Canadian government's choice of a 40MHz set-aside can thus be seen as a middle ground approach.

Finally, we consider by what percentage aggregate profits would have changed if the eight largest bidders in terms of initial eligibility won each of the eight blocks nationwide.[23] This assignment can be argued to be efficient from the point of view of awarding the most spectrum nationwide to those firms with the highest eligibility. This will also lead to the maximal value of *geo*. Both $e\sum MHz \times pop$ and geo^M should increase, though they will not be maximal. Finally, the effect on *spec* and $comp^H$ is, *a priori*, ambiguous. Note that in this scenario, 50MHz of AWS spectrum is allocated to new entrants, rather than the 40MHz of the actual set-aside.

Remark 3. *We note here that the precise allocations that would have arisen under alternative auction rules (e.g., no set-aside) are difficult to predict with certainty. The very presence of a set-aside likely led to increased participation in the auction because it increases the chances that a new entrant could obtain spectrum on favorable terms.*[24] *This is one of the main limitations faced by applied structural papers analyzing multi-unit auctions: we are unable to compute equilibria in multi-unit ascending auctions with complementarities under alternative rules about set-asides.*

[22] Recall from Table 1 that the entrants received a substantial implicit subsidy due to the set-aside. Moreover, as evidenced through the attempts of Rogers and Telus to acquire spectrum from the incumbents (directly via takeovers by Telus or indirectly via spectrum purchases by Rogers (Sturgeon, 2013, Dobby, 2013, Trichur and Silcoff, 2013)), there is some evidence that the incumbents were unable to purchase all of the spectrum that they desired. Therefore, we feel that this is a plausible assumption.

[23] Those bidders with the highest eligibility were allocated a 20MHz license, while those with less were allocated a 10 MHz license and, finally, the bidder with the 8^{th} highest initial eligibility won the 5MHz I block. Licenses that went unsold in the actual auction were excluded from the counterfactual analysis.

[24] For example, Google committed to participate in the U.S. 700MHz auction and bid a minimum of $4.6 billion if the FCC adopted an "open" policy towards devices and spectrum use (Brusco, Lopomo, and Marx, 2009).

Before doing this, Table 5 reports the package characteristics of the four alternative scenarios. Panels (a)–(d) contains results for each of the four aforementioned scenarios. Finally, panel (e) summarizes the package characteristics based on the actual allocation in the auction. As can be seen, going from the actual allocation to a scenario in which the eight largest bidders won increases, $e \sum MHz \times pop$ by approximately 23% and geo^M by a more modest 5.6%. Furthermore, our measure of competition is little changed. Next, comparing the scenario in which a single bidder wins with the three other alternatives, we see that geo^M, *spec* and $elig \sum MHz \times pop$ are maximal and competition is reduced to 0 when a single bidder wins. On the other hand, because all spectrum is allocated to a single winner, unweighted geographic complementarities are minimized.

Table 6 reports the percentage change in aggregate profits (from the actual allocation) for each of our four alternative allocations; thus positive numbers indicate that the alternative scenario would have increased profits, while negative numbers indicate that the alternative scenario would have decreased profits. We report results using our maximum match estimates for each of the eight different specifications. The second column reports the percentage chance in aggregate profits in the case that a single bidder wins, while the third, fourth and fifth columns do the same under the no set-aside, all set-aside and assortative matching counterfactuals, respectively. For the no set-aside scenario, we assumed that the spectrum would be divided amongst bidders in proportion to their share of pre-existing spectrum in each region. The assortative matching scenario allocates each of the eight spectrum blocks to bidders in order of their initial eligibility (with the largest bidders receiving 20MHz, intermediate bidders receiving 10MHz of AWS spectrum and the smallest bidders receiving the G and I blocks).

When judging whether the auction was successful – at least in terms of aggregate profits – Table 6 suggests that the answer depends crucially on whether one believes that geographic complementarities are best captured by *geo* or by geo^M. The efficiency gain using unweighted geographic complementarities ranges from 24.31 to 91.05%, while when using spectrum-weighted complementarities, the range is from 8.98 to 32.92%. The former case leads to results which are roughly similar to Fox and Bajari (2013), and would indicate an inefficient auction.

As we have said above, we feel that there is a compelling case to be made that spectrum-weighted geographic complementarities is the appropriate measure. For example, look back at Table 2 and consider bidders 13 and 15. While both won licenses covering the entire country (hence, $geo = 1$ for both), the unweighted measure fails to capture the fact that bidder 13 won 20MHz nationwide, while bidder 15 won a combination of 10MHz and 20MHz licenses. Therefore, while bidder 13 can provide a consistent level of service across the entire country, bidder 15's service offerings may be limited in those regions where it only won 10MHz of spectrum, which should lead to lower complementarities. The spectrum-weighted measure, geo^M, captures precisely this intuition.

Therefore, if we focus on only those specifications which use spectrum-weighted geographic complementarities, 1(b)–4(b), then it would appear that the auction was not wildly inefficient (and there is less variability across the scenarios). That being said, there is still a large difference depending on whether or not one separately controls for the amount of spectrum won via *spec*.

Table 5: Package Characteristics Under Counterfactual Scenarios

(a) Single Bidder Wins

Bidder	Status	$elig \sum MHz \times pop$	geo	geo^M	$spec$	$comp^H$
13	Incumbent	19.05	1	100.25	10053	0

(b) No Set-Aside, Status Quo Spectrum Shares

Bidder	Status	$elig \sum MHz \times pop$	geo	geo^M	$spec$	$comp^H$
2	Entrant	0.13	0.033	0.93	28.8	0.011
5	Incumbent	1.83	0.927	25.82	743.1	0.275
13	Incumbent	9.34	1	49.16	2342.8	0.134
14	Entrant	0.01	0.028	0.78	25.7	0.010
15	Incumbent	2.04	1	23.27	546.0	0.322
Total		13.35	2.989	99.95	3776.4	0.752

(c) All Set-Aside, Spectrum Shares Proportional to Entrant Winning Shares

Bidder	Status	$elig \sum MHz \times pop$	geo	geo^M	$spec$	$comp^H$
1	Entrant	1.76	0.300	11.89	516.7	0.057
2	Entrant	0.85	0.033	1.89	119.1	0.004
3	Entrant	2.16	0.587	11.73	235.7	0.236
4	Entrant	0.45	0.302	21.20	1706.6	0.063
6	Entrant	2.00	0.012	0.24	13.9	0.014
7	Entrant	0.70	0.096	5.31	424.8	0.024
8	Entrant	3.00	0	0	1.4	0.001
9	Entrant	2.60	0.439	9.66	268.4	0.127
10	Entrant	1.64	0.737	21.22	725.6	0.196
11	Entrant	2.78	0.228	4.54	91.2	0.063
12	Entrant	3.00	0	0	1.8	0.001
14	Entrant	0.50	0.028	1.85	144.5	0.002
Total		13.35	2.762	89.53	4249.7	0.788

(d) Assortative Matching

Bidder	Status	$elig \sum MHz \times pop$	geo	geo^M	$spec$	$comp^H$
3	Entrant	0.0467	0.085	0.424	3.75	0.023
5	Entrant	0.6716	0.922	9.216	94.95	0.141
15	Incumbent	0.877	1	10	100	0.149
10	Incumbent	0.8921	1	10	100	0.149
4	Entrant	1.1693	1	10	100	0.149
2	Entrant	2.4923	1	20	400	0.119
1	Entrant	2.9007	1	20	400	0.119
13	Incumbent	3.800	1	20	400	0.119
Total		12.85	7.006	99.64	1598.70	0.970

(e) Overall Actual Package Characteristics (from Table 2)

	$elig \sum MHz \times pop$	geo	geo^M	$spec$	$comp^H$
Total	10.450	5.628	94.375	2000.39	0.974

Table 6: PERCENTAGE CHANGE IN PROFIT FROM ESTIMATED PROFITS UNDER ALTERNATIVE ALLOCATION SCENARIOS

Specification	Single Winner	No Set-Aside	All Set-Aside	Assortative Matching
1(a)	-63.40	-38.36	-47.29	24.31
2(a)	75.83	-2.65	2.33	9.96
3(a)	-8.47	-99.58	-130.98	91.05
4(a)	48.87	-50.15	-62.58	51.54
1(b)	9.49	6.84	-5.73	6.32
2(b)	32.92	11.50	2.72	3.89
3(b)	8.98	6.66	-4.87	5.79
4(b)	28.18	10.97	-0.02	5.16

Highlighted cells represent the counterfactual scenario which leads to the greatest increase in profits for the specification.

If we exclude *spec*, then the efficiency gain using specification 1(b) is 9.49% (or approximately \$404 million). On the other hand, if we include *spec*, as in specifications 2(b) and 4(b), then the efficiency gain is approximately 30% (or \$1.28 billion).[25] Of this, between 52 and 82% of the gain is due to the dramatic increase in the value of *spec* going from the actual allocation to the alternative allocation of a single winner. The increase in geo^M is responsible for another 18 to 23% of the efficiency gain. The remaining portion is picked up by the increase in $e \sum MHz \times pop$ and the reduction in competition.

While a single bidder winning all of the spectrum may represent the upper bound on auction efficiency, it is also an unlikely outcome even in the absence of the auction set-aside. As we said, we believe that the most plausible outcome in the absence of the auction set-aside is that the existing providers would divide the spectrum amongst themselves, roughly in proportion to their existing shares. This scenario would lead to an efficiency gain of between 6.7 and 11.7%, or approximately \$497 million at the upper bound of this range. Notice also the two models that include *spec* (2(b) and 4(b)) have efficiency losses that are larger than the same models without *spec* (1(b) and 3(b)). This is intuitive given that *spec* interacts population in a given tier 3 region with MHz squared. Taking the additional MHz away from the larger firms (via the set-aside) reduces the gains from acquiring more spectrum. This is also the case for the single winner and all set-aside scenarios.[26]

Finally, observe that our results based on spectrum-weighted complementarities suggests that an assortative allocation procedure in which the 8 largest bidders were allocated all the spectrum — effectively increasing the set-aside to 50MHz and also guaranteeing three entrants with national footprints, would have increased aggregate profits by a more modest amount. However, setting

[25]Even this amount is likely over-stated because it fails to take into account that the other two incumbents already have spectrum in other ranges. Therefore, while competition would be reduced, it would not disappear entirely.

[26]The opposite is true in the assortative matching scenario. This is intuitive as well since the assortative matching scenario is the closest setting to what actually happened and so the gains from acquiring additional spectrum are much less in this setting relative to the auction setting.

aside all spectrum to new entrants, and awarding licenses based on the shares won in the actual auction, would, generally, have made the auction even less efficient.

7 Discussion

The analysis above suggests that for a broad range of alternative spectrum allocations that there was an efficiency loss. However, two important questions beyond focusing on auction efficiency exist. First, has social welfare increased by more than that amount due to the presence of the new entrants? Second, are the welfare gains sustainable over the long term? Answering the first question is complicated by the fact that it is difficult, with the available data, to identify changes (e.g., in prices) that were caused by the increased competition due to new entry rather than other structural changes that took place concurrently such as the rise of the smartphone and the importance of data services. By its forward-looking nature, any answer to the second question is inherently speculative.

7.1 Did The Set-Aside Increase Social Welfare?

To shed some light on the issue of social welfare we briefly consider the evolution of two metrics, which likely influence consumer welfare – consumer choice and prices – since the AWS auction. On the issue of consumer choice, we can concretely say that consumers have benefited due to increased choice. Since the auction, five new entrants have begun offering services: Wind Mobile, Mobilicity, Public Mobile, Vidéotron and, most recently, Eastlink Wireless. Wind and Mobilicity have operations in most large Canadian cities, while Public Mobile focused its business on the Toronto to Montreal corridor, Vidéotron operates exclusively in Quebec, and Eastlink offers service exclusively in Atlantic Canada. As of the end of 2013, the new entrants combined have over 1 million subscribers.[27] Thus, consumer choice has increased. Moreover, the approximately 1 million subscribers have certainly benefited from entry because they *could have* obtained wireless services from one of the incumbents but chose not to.

Turn now to the question of whether consumers in general – not just customers of new entrants – have benefited from lower prices. This is a much more difficult question. For example, in trying to argue that consumers have benefited from increased competition, CIBC (2011) reports that the average revenue per user (ARPU) for voice services for Rogers has declined by 17% since the third quarter of 2008. However, two things happened since 2008: the AWS auction **and** a shift away from voice-only plans to data intensive smartphones; therefore, it is difficult to determine causation.

In Table 7(a), we report the blended average revenue per user for Rogers, Bell and Telus in Canada, while Table 7(b) reports comparable figures for Verizon and AT&T in the United States. The U.S. carriers may serve as a comparison group, since the U.S. saw the same technological shift in the wireless market but there were no serious efforts made to increase competition.[28] Thus

[27] Sources: http://cwta.ca/wordpress/wp-content/uploads/2011/11/SubscribersStats_en_2011_Q3.pdf, http://business.financialpost.com/2011/11/18/mobilicity-shakes-up-management/ and http://wirereport.ca/reports/content/13185-public_mobile_passes_150000_subscribers.

[28] Blended ARPU is a weighted average of ARPU for pre- and post-paid customers and can, itself, be divided into

Table 7: Average Revenue Per User for Canadian and U.S. Carriers

(a) Canadian Incumbents

	Rogers			Telus			Bell
Year	Blended	Data	Voice	Blended	Data	Voice	Blended
2012	\$59.79	\$24.22	\$35.57	\$60.38	\$23.99	\$36.40	\$55.82
2011	\$60.20	\$21.21	\$38.99	\$59.09	\$19.88	\$39.22	\$53.55
2010	\$62.62	\$17.60	\$45.02	\$57.63	\$14.37	\$43.26	\$52.03
2009	\$63.59	\$13.93	\$49.66	\$58.46	\$11.87	\$46.59	\$51.70
2008	\$64.34	\$10.55	\$53.79	\$62.73	\$9.81	\$52.92	\$54.29

(b) U.S. Providers

	Verizon		AT&T	
Year	Blended	Voice	Blended	Voice
2012	\$54.10	\$30.16	\$46.99	\$26.40
2011	\$52.68	\$31.63	\$47.77	\$29.25
2010	\$50.53	\$32.77	\$49.68	\$32.82
2009	\$50.78	\$35.60	\$50.68	\$35.98
2008	\$51.71		\$50.39†	

The Canadian data comes from annual shareholder reports of the respective companies. The U.S. data comes from `http://www.fiercewireless.com`.
† This only averages over the first and second quarter of the year.

differences between Canadian and American carriers' changes in ARPU *could possibly* be due to the enhanced competitive structure brought about by the set-aside in Canada. Using 2009 as the base year, to facilitate comparison between Canadian and U.S. carriers, we see that Rogers' voice ARPU dropped by 28%, while Telus saw a 22% decline. In contrast, the declines in voice ARPU for AT&T and Verizon were 27% and 15%, respectively. Thus, voice ARPU may have dropped by a larger percentage among Canadian carriers than their U.S. counterparts.

If, instead, we look at blended ARPU, a similar picture emerges. While in Canada Rogers and Telus saw declines (from 2008 to 2012) in blended ARPU of 7.1% and 3.7%, respectively, Bell's blended ARPU increased by 2.8%. In the United States, Verizon's blended ARPU increased by 4.6% while AT&T's declined by 6.7%. Just as with voice ARPU, it may have been that Canadian customers saw more favorable changes in blended ARPU than in the U.S., and part of this may be attributable to the increased competition brought about by the set-aside.[29]

Given the data limitations, it would be presumptuous to try to compute the savings to consumers that is attributable to increased competition. However, we simply note that the data suggest that

voice and data components, which are also reported in Table 7, when the data could be found. We were unable to break up Bell's blended ARPU into voice and data components, and we could not find voice ARPU for the U.S. carriers for 2008.

[29] For example, one could argue that Rogers and AT&T are comparable because both companies were the original providers of Apple's iPhone and, therefore, faced many of the same pressures. The fact that Rogers' ARPU declined by somewhat more than AT&T may be due to increased competition.

it is, at least, possible that consumers have benefited due to lower prices. If so, then since the lower prices represent a flow variable that will accumulate over time, social welfare may eventually be higher, *provided that the increase in competition is sustainable over the long term.*

Although choice has increased and prices may have come down as a result of the AWS auction, there are other consequences that may have worked to reduce social welfare. The main factor is that a non-negligible amount of spectrum remains un-deployed. For example, Shaw, decided not to launch its own network and instead entered into an agreement with Rogers to sell its spectrum to them once the 5 year period in which incumbents are prevented from purchasing set-aside spectrum expires in early 2014 (Sturgeon, 2013). Similarly, Vidéotron won spectrum in the lucrative region of Southern Ontario, but has also left this spectrum un-deployed and has also attempted to sell this to Rogers. This means that a significant amount of spectrum has sat idle for 5 years, and may continue to do so if the federal government blocks these spectrum transfers. Hazlett and Munoz (2009) argue that such idle spectrum is a substantial source of inefficiency. Additionally, the fact that incumbents were not able to win as much spectrum as they would have liked, may have played a role in the decision by Bell and Telus to enter into a network sharing agreement, which could also limit competition and reduce innovation (Church and Wilkins, 2013).

7.2 Is Enhanced Competition Sustainable?

We now turn to the inherently speculative question of whether the new status quo that emerged out of the auction is sustainable. As of the end of 2013, Public Mobile, Mobilicity and Wind were all experiencing financial difficulties and were either for sale or already sold. Public Mobile was acquired by the incumbent, Telus (Dobby, 2013); Telus also tried to acquire Mobilicity but the Canadian government blocked the sale (Trichur and Silcoff, 2013). Finally, the U.S. provider Verizon was in talks to purchase either Mobilicity, Wind or both, but eventually decided against entering the Canadian market (Chase, Erman, and Trichur, 2013).

Given the financial difficulty of many new entrants and attempts to sell unused spectrum by others, it is hard to imagine that the altered landscape created by the auction will prove to be sustainable. With the exception of Vidéotron, which has 40MHz of spectrum across Quebec, all of the other entrants have at most 20MHz of spectrum, as compared to at least 50MHz held by each incumbent. Given the dramatic shift towards smartphones, particularly in Canada (see, e.g., Church and Wilkins (2013)) this is inadequate to meet the demands of consumers and may have meant higher fixed and variable costs for new entrants (Hazlett, Munoz, and Avanzini, 2012, ¶93). This competitive disadvantage due to lack of scale is likely to continue since neither Wind nor Mobilicity participated in the recent 700MHz auction; however, Vidéotron did win spectrum outside of Quebec, raising the possibility that it may expand into a national carrier (Pellegrini and Batcho-Lino, 2014).

The diverging fortunes of Vidéotron and of Wind, Mobilicty and Public Mobile suggests that the set-aside policy may have been correct *per se* but that its implementation was flawed. For example, rather than having three different blocks of spectrum, totaling 40MHz, it is possible that a single block of 40MHz would have allowed new entrants to achieve a minimum scale necessary to provide both high quality data and voice services. The experience of Canada could suggest a familiar cautionary tale whereby governments should be cautious in their approach to spectrum policy when the technological landscape is uncertain (see also Hazlett and Munoz (2009) and Hazlett, Munoz, and Avanzini (2012) for a further perspective). The current uncertainty about the viability of the new entrants is reminiscent of 1995. In that year, two new entrants were awarded 30MHz of PCS spectrum; however, competition was short-lived as one of the new entrants was purchased by Telus in 2000, and the other was purchased by Rogers in 2004.

8 Conclusions

Prior to Industry Canada's AWS auction, a stated goal was to increase competition in the wireless phone industry. To achieve this goal Industry Canada employed a set-aside policy to prevent incumbents from bidding in all 8 blocks of available spectrum. Set-aside auctions are one of a cluster of regulatory policies available to auctioneers who may wish to achieve certain "desirable" outcomes. Unfortunately, even with this appeal, very little empirical work exists exploring just how beneficial these policies are, and even less structural work exists in this arena. Our study is one of the first to structurally investigate the ramifications of such a policy for auctioning spectrum. We use recently developed pairwise matching estimators and the notion of pairwise stability to estimate the parameters of the telecommunications firms' profit function. These estimates were then used to consider alternative spectrum allocation schemes to determine the efficacy of the set-aside for Industry Canada's stated goals of increasing competition.

Our results suggest that auction revenue may have increased by as much as \$1.28 billion under alternative scenarios, though a more likely scenario, in the absence of the set-aside, the likely outcome was a "status quo" with no new entry and similar market shares. In this case, our results suggest an efficiency loss on the order of \$400 – 500 million. As we have argued, while this is a non-negligible amount of money, to the extent that enhanced competition is sustainable, it is plausible that consumers could benefit by more than this amount. However, recent events have made clear that, in their current state, the most prominent new entrants' long term financial viability is in question. Furthermore, despite auction rules favorable to new entrants, few chose to participate in the most recent 700MHz auction, thereby perpetuating their competitive disadvantage. In fact, future research along these lines could focus on the changing telecommunications landscape from the AWS auction and the 700 MHz auction contrasting differences in auction format: several differences include a spectrum cap instead of a set-aside, a combinatorial clock auction instead of a simultaneous multiple round auction, allowing anonymous bids as well as structuring all licenses at the tier 2 level. Another interesting extension would be to study bidder entry; whereas the AWS auction had 21 bidders submit bids, only 10 bidders submitted bids in the 700 MHz auction.

Finally, if we compare our results to Olivares, Weintraub, Epstein, and Yung's 2012 study of the Chilean school lunch combinatorial auctions, we reach a similar conclusion about the tradeoff between welfare and competition if the bid caps/set-aside were removed. Specifically, Olivares, Weintraub, Epstein, and Yung (2012, p. 1479) note that "the potential downside of removing market share constraints – reducing the intensity of local competition through a concentration of the supplier base – could outweigh the benefit of further exploiting cost synergies."

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A Bidding Behaviour: Signaling & Implicit Collusion (e-Companion)

Given the transparency of spectrum auctions in practice (*e.g.,* all bids, including the identity of the bidder, are made public at the conclusion of each round), bidders may have many signaling opportunities. There are several reasons why bidders might wish to signal. For example, to coordinate a mutual demand reduction, to signal strength or to signal a desire to obtain a specific set of licenses. Signaling strength or a desire to win a particular license may be accomplished by so-called jump bids, while an attempt to coordinate bidding may be accomplished by what we call *tit-for-tat* bids.

A.1 Jump Bids

Bidding in the AWS auction was "yes/no". That is, for each license, the auction software listed the current price p of the standing high bidder and a price $p' > p$. If bidders are willing to pay p' for the license, then they select "yes" for that particular license. The bid, p, of the standing high bidder is automatically carried forward to the next round. However, the standing high bidder may also choose to bid p' if they so desire. Such a bid is called a jump bid. By placing a jump bid, a bidder may be signaling to others that it has a high valuation for that license in an attempt to discourage others from competing for it.

In this auction, out of the 10,037 total bids placed, 107 of them were jump bids — 58 of which were unique.[30] However, it is difficult to determine conclusively that these were done with the intention of signaling. For example, for 56 of the 107 jump bids, there was at least one other bid placed on the license. Therefore, the jump bid may have been placed with an eye towards coming out on top of a tie-break.[31] Furthermore, placing jump bids did not ensure that a bidder would eventually win the particular license — in only 20 instances did the jump bidder eventually win and in only two cases was a jump bid the final bid placed. Indeed, it seems that one use for jump bids was to prevent the auction from closing prematurely before bidders had achieved their desired footprint. For example, in two rounds a jump bid was the only bid placed and in the final 100 rounds of the auction, jump bids represented approximately 10% of the total number of bids. By placing a jump bid, and keeping the auction open, it would give them more time to determine their bidding strategy in the final, potentially decisive, rounds. For example, in rounds 236 and 243, Rogers placed the only bid in each of those rounds with a jump bid — notably on a low-priced license in the I block. If we compare the packages of bids held by Rogers in rounds 236 and 243 with its final allocation at the end of the auction, we see that their were 14 licenses that Rogers held in the earlier rounds, but eventually lost and there are 17 licenses that they were not currently winning in one or both of the earlier rounds, that they eventually went on to win. Thus, it would seem that Rogers consciously tried to keep the auction from closing in order to have more time to construct its most desired package of licenses.

A.2 Tit-For-Tat Bids

Consider now tit-for-tat bidding, which we define as follows. Let $S(a,T)$ denote the set of licenses for which bidder a is the standing high bidder in round T. Let $S(a,T,t)$ denote the set of licenses for which bidder a either bid on, or was the standing high bidder on, in rounds $T-t, T-t+1, \ldots, T$. Then suppose that bidder b outbids bidder a in round T on some set $O(b) \subseteq S(a,T)$. We will say that bidder a places a tit-for-tat bid against bidder b if, in round $T+1$, bidder a bids on licenses in the set $S(b,T+1) \setminus S(a,T,t)$ (i.e., bidder a bids on those licenses that bidder b is the standing high bidder on at the beginning of round $T+1$, and which bidder a has not bid on, nor was the standing high bidder, in the previous t periods).

Conservatively, if we take $t = T$ (i.e., so that the bidder who places a tit-for-tat bid has never bid on that particular license until round T), then the number of instances of tit-for-tat bidding is 336. However, in many of these cases it is difficult to say that they were placed with an eye towards signaling. For example, 111 of the bids in question involved bids between the incumbents, primarily on licenses in the A, E and F blocks. Since the incumbents all appeared interested in

[30]There were instances in which the same bidder placed multiple jump bids on the same license in different periods.

[31]For example, near the end of the auction, prices may be coming close to one's valuation. Therefore, placing a jump bid (and winning a tie-break) may allow the bidder to win the license and save one bid increment, which, in this auction was at least 4%.

winning a national footprint, it is unlikely that tit-for-tat bidding would be a sensible or effective strategy. Instead, they may be motivated by other reasons such as price arbitrage (i.e., perhaps the license in question is the cheapest one in that region).

On the other hand, there are some instances in which apparent tit-for-tat bids did appear to represent attempts to signal to other bidders one's intentions. We highlight three such examples. First, in round 19, Eastlink outbid Shaw on license 209b. In the next round, Shaw placed a bid on license 202b, which, it is arguable, Shaw had no interest in obtaining because it did not appear to be consistent with Shaw's other bids.[32] The exact same scenario played out again in rounds 71 and 72. Although this seems like a clear case of signaling, it appears that it was unsuccessful since Eastlink eventually won both licenses 209b and 202b.

Second, in round 71, Wind Mobile outbid Vidéotron on a number of licenses in Quebec. In the following round, Vidéotron outbid Wind Mobile on licenses in Atlantic and Western Canada (i.e., 201c, 203c, 302d, 303d, 304d, 339d and 340d), all of which Vidéotron had never bid on before that round (and likely had little interest in actually winning, since Vidéotron is a company whose primary interest lies in the province of Québec). Interestingly, after round 72, while Wind Mobile continued to seek out a foothold in Quebec, it only placed bids for non-set-aside licenses.

Finally, to give an example where incumbents may have engaged in tit-for-tat bidding with an attempt to signal, we note that in round 66 Bell outbid licenses held by Rogers. In the following round, Rogers placed bids on licenses 318f, 319f and 320f. This occurred under the following conditions (i) Rogers had never previously bid on these licenses, (ii) Rogers was the current standing high bidder on the equivalent licenses in the A block and (iii) the current prices were substantially higher in the F block than in the A block.

Although the evidence that jump bids were used to signal strength appears to be somewhat limited, the evidence in favor of tit-for-tat bidding does appear somewhat more conclusive. Given this, it is important that the empirical strategy that we employ remains robust to such behavior. As Fox and Bajari (2013) discuss extensively, the notion of pairwise stability in matches (i.e., that two bidders bidders would not benefit from trading one license with each other) is very likely to be satisfied even in such cases. This is discussed in greater detail in Section 4.1 in the main text.

B Reduced Form Analysis of Auction Prices (e-Companion)

Table 8 reports the results of a series of regressions designed to discern the impact of certain auction features and covariates on prices. The dependent variable is the price per MHz$\times$pop of licenses sold. Because the non-AWS spectrum was relatively less attractive, we drop the G and I blocks from this analysis. We consider two types of explanatory variables: (1) license characteristics (e.g., population density of the license area) and (2) strategic concerns. We consider two variables that may capture strategic concerns. First, the share of pre-existing spectrum held by a bidder in any

[32]See the article, "Winning air waves with poker-like skills; Corporate strategy. How Shaw Communications broke into the mobile phone business without losing its shirt," *The Globe and Mail*, July 26, 2008.

region may affect its willingness to pay for more spectrum in that region. Second, if geographic complementarities are present, then they could affect the price paid for the license. We implement this along the lines of Ausubel, Cramton, McAfee, and McMillan (1997). Specifically, we construct a variable which, for each license i, calculates the population-weighted spectrum won in neighboring licenses by the *second-highest bidder* for license i. The intuition is that if the winner of adjacent spectrum benefits from geographic complementarities, then she may bid up the price for that license, forcing the winner to pay more.

Table 8: Regression Results: Explaining Final Prices (AWS Blocks Only). Dependent Variable is Price per MHz×pop

	(1)	(2)	(3)	(4)
$\frac{\text{population in license area}}{\text{Canadian population}}$	8.321***	8.326***	8.299***	8.304***
	[1.591]	[1.618]	[1.501]	[1.525]
$\ln\left(\frac{\text{population in license area}}{\text{size of license are in } km^2}\right)$	0.053**	0.053***	0.052**	0.052***
	[0.020]	[0.015]	[0.020]	[0.015]
$\mathbf{1}[\texttt{set-aside}]$	-0.932***	-0.932***	-0.734**	-0.746**
	[0.261]	[0.261]	[0.302]	[0.299]
$\mathbf{1}[\texttt{20 MHz}]$	-0.006	-0.009	-0.101**	-0.098**
	[0.050]	[0.043]	[0.033]	[0.035]
$\mathbf{1}[\texttt{tier} = 3]$	0.467***	0.465***	0.450***	0.450***
	[0.107]	[0.108]	[0.105]	[0.106]
Pre-existing MHz		1.570		1.215
		[1.221]		[1.031]
Second Highest Bidder's Share			1.196*	1.123*
of Adjacent Spectrum			[0.567]	[0.547]
Constant	1.022***	1.024***	0.819***	0.832***
	[0.229]	[0.230]	[0.261]	[0.256]
Adjusted R^2	0.3744	0.3802	0.3974	0.3998
N	264	264	264	264

Standard errors (accounting for clustering at the bidder level) in brackets. We also included bidder fixed-effects but do not report them here.
*, ** and *** denote significance at the 10, 5 and 1% level, respectively.

As can be seen, more populous and more densely populated areas commanded higher normalized prices. Moreover, set-aside spectrum sold at a significant discount. It is interesting to note that the coefficient on the indicator for 20 MHz is negative, and in some specifications, conventional confidence intervals contain 0, which could be indicative of budget constraints playing a role in bidding. Concerning our two strategic variables, we see that the amount of pre-existing MHz held by the winner of license i had a positive effect on the price that was paid for the license, but this impact is estimated with relative imprecision with respect to the other key variables in the model. Thus, we cannot rule out the fact that pre-existing MHz did not have, on average, an impact on final license prices. Finally, and importantly for our subsequent structural analysis, there is some evidence that geographic complementarities exist. The larger the share of adjacent spectrum won by the second highest bidder, the higher is the price paid by the eventual winner of a license.