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Abstract

Scarce radio spectrum is assigned to mobile network operators (MNOs) by national regulatory authorities (NRAs). Spectrum is usually assigned by beauty contest or an auction. The process requires that winners make a payment to the government. MNOs seek scarce spectrum to enable the provision of wireless services for profit. While MNOs are imperfectly aware of their costs, NRAs rely solely on MNOs for this information. As such, NRAs set spectrum assignment conditions (including minimum bid price) largely ignorant of MNO operating conditions. This study examines the performance of 3G auction outcomes in terms of the prices paid by winners via an econometric analysis of a unique sample of national 3G spectrum auctions. These winning bids depend on national and mobile market conditions, spectrum package attributes, license process, and post-award operator requirements. Finally, model estimation accounts for the censored nature of these data.

Keywords

Mobile telephone markets, spectrum allocation, spectrum bid price

JEL Classification: D44; L96

1. Introduction[*]

Radio spectrum is a scarce (non-depletable and non-storable natural) resource that is exclusively licensed (Faulhaber and Farber, 2002; Faulhaber, 2006). Under International Telecommunication Union (ITU) guidance scarce spectrum is allocated to mobile network operators (MNOs) by national regulatory authorities (NRAs). Historically, user assignment is by government fiat. However, in the 1990s, faced with emerging competitive mobile telephone markets a more arms-length process of spectrum allocation developed (McMillan, 1994; Gans et al., 2005).

In particular, NRA spectrum licensing policy must decide on: (a) whether to set a single standard (or allow technological system competition); (b) how many licenses to award; and (c) the method to award licenses. With mobile telecommunications licenses awarded initially on a first-come-first-serve basis to (incumbent) fixed-line telecommunications operators, subsequent licence awards are made by auction or through an administrative tender procedure (e.g., 'beauty contest'), possibly including a licence fee (Gruber, 2001: 62).[1] Beauty contests require that MNOs submit plans or bids to NRAs including spectrum use plans. After hearing proposals, NRAs award spectrum to MNOs that present the most 'attractive' proposals.[2] With a lottery, regulatory authorities randomly select licence winners from among network operator submitted applications.[3]

The principal argument for auction-based spectrum allocation is that it promotes efficient use via competition among applicants. That is, operators with higher valuations are likely to bid more for the spectrum resource. Another advantage of auctions is that this competition is not wasteful as spectrum licence revenues substitute for distortionary taxation.[4] Finally, auctions are a more transparent means to assign licenses than administrative processes (Cramton, 2002: 608).[5] For NRA allocations to be efficient (accurately reflect the true economic value of the spectrum) auctions must be designed carefully.[6] A complication is that auctions are embedded within administrative processes that specify the amount of spectrum allocated (and other spectrum package attributes), award conditions, and post-

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1 Until recently spectrum is made available without charge. The approach is inefficient, e.g., idle 'white' spectrum or rigid allocations do not respond to changes in demand (Hazlett, 2001). Alternative spectrum fee options include: once off upfront, recurring lease and real-time congestion fees. Upfront payments presently dominate (Bauer, 2003).

2 Beauty contests suffer from several problems. First, they are extremely slow and wasteful. Competitors spend vast sums trying to influence the regulator's decisions. Second, beauty contests lack transparency (Cramton, 2002: 607).

3 Since spectrum licences are valuable there is an incentive for many firms to apply. Large numbers of applicants waste resources in creating and processing applications. Moreover, the winners are not necessarily best suited to provide a service (Cramton, 2002: 607-8).

4 Typical estimates are that deadweight losses are between 17 and 56 cents for every extra $1 raised in taxes (Ballard et al., 1985).

5 Despite their virtues, standard auctions at best ensure that the bidder with the highest private value wins, rather than the bidder with the highest social value. Private and social values can diverge in these auctions because the winners will be competing in a marketplace. One collection of winners may lead to a more collusive industry structure. For example, a license may be worth more to an incumbent than a new entrant, simply because of the greater market power the incumbent would enjoy without the new entrant (Cramton, 2002: 608).

6 However, it is not straightforward translating theoretically-efficient designs into practice with recent auctions seriously flawed (Klemperer, 2002b).

award financial and network performance operator obligations. For instance, 'too high' up-front licence fees (spectrum bid price) either forces the exit of firms or provides a signal for post-entry collusion (Gruber, 2001, 2002).[7] Additionally, high licence fees constrain subsequent network investment when financed through debt, with higher capital costs leading to slower network expansion.

While operator bidding is driven by expected profit considerations and not societal welfare (Klemperer, 2002a: 177), efficient spectrum assignment (or maximizing the sum of the valuations of operators awarded the licenses) is the principal aim of most NRAs (Klemperer, 2002b: 844).[8] However, whether an auction allocation is efficient cannot be directly observed, only whether the auction process is apparently competitive (based on the number of bidders and their activity) and the winning spectrum bid price (Klemperer, 2002b: 844). This study examines 3G spectrum award outcomes in terms of the spectrum winning bids paid by winners through the econometric analysis of a unique sample of national 3G spectrum allocations. These spectrum winning bids are modeled as depending on national economic and mobile market conditions, spectrum package attributes, the licensing process, and post-award operator obligations. Finally, the analysis explicitly takes into account the censored nature of these data, viz., only in certain successful award processes are non-zero spectrum winning bids observed.

The paper is structured as follows. Section 2 reviews selected advanced economy mobile telephony and spectrum assignment process evolution, while Section 3 lists factors that potentially affect MNO spectrum valuations. In Section 4 descriptive information concerning sample data is provided, and variables in the empirical analysis are defined. Prior to model estimation, national 3G award sample descriptive statistics are calculated in Section 5. The censored regression model used for econometric estimation is specified in Section 6, while estimation results are reported in Section 7. A final section suggests some modeling extensions.

2. Mobile Telephony and Spectrum Assignment

Mobile communications rapidly evolved since the 1980s introduction of (voice only) first generation analogue systems (Gruber and Hoenicke, 1999). This technology is characterized by relatively low network capacity and large handset size (Grant, 2005). Subsequent second generation (2G) technology developments are in response to demand for enhanced voice and data services (Gruber and Hoenicke, 1999). Digitally-based 2G systems also benefited from unified European standards. However, the European Global System for Mobile Communications (GSM) and the United States (US) based Time Division Multiple Access (TDMA) and Code Division Multiple Access (CDMA) systems remained incompatible, limiting opportunity for global roaming (ITU, 2003).[9] Despite this limitation, the 2G mobile to fixed-line penetration ratio rose rapidly in advanced economies (see Table 1).

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7 It is widely accepted that once the right to operate in a market is obtained entry costs are sunk and therefore inconsequential for subsequent pricing and investment decisions. License fees are important for later firm decisions only in as far as they appropriately reflect the ongoing opportunity costs of spectrum. Deviations between license fees and the opportunity costs (both over- and underpayment) only affect the distribution of rents between the shareholders and the public sector (Cave and Valletti, 2000). However, this line of reasoning holds only if stringent assumptions as to the competitiveness of the mobile market, the working of capital markets, and the dynamics of sector adjustment hold. If these assumptions are modified to better reflect the institutional and economic features of the mobile industry, license fees may have less benign effects on sector evolution. The potential distortion of pricing and investment decisions is higher for fees that are fixed upfront, as they lock in the sector outlook at one moment in time without opportunities to adjust once more information on the true market conditions is revealed (Noam, 1998).

8 That is, operators only submit bids when their expected profits are non-negative (Bauer, 2003).

9 GSM and TDMA divide a carrier channel into time slots, digitally encoding the signal onto these time slots. CDMA uses spread-spectrum technology, as used in 3G systems (Cabral and Salant, 2009: 2).

Table 1. Ratio of Mobile to Fixed-line Penetration

Region/Country	1992	2002
EU	0.04	1.58
Japan	0.03	1.33
US	0.08	0.75

Note: Penetration is the number of subscribers per 100 populations for 1G and 2G systems. *Source*: ITU World Telecommunications Indicators Database (2008).

Greater European (1.58) relative to US (0.75) growth is in part explained by the European Union (EU) delegating standard setting to a central body, the European Technical Standards Institute. By contrast, the US Federal Communications Commission grants operators the right to select standards, resulting in handset incompatibility (Gandal et al., 2003). More recent, third generation (3G) mobile telephony developments address the need for global compatibility, multi-media services provision and greater speed.

Electromagnetic spectrum is required to provide wireless communication services. ITU World Radio Conferences (WRCs) allocate spectrum bands to specific uses. In 1992, the WRC IMT-2000 project defines standards for the deployment of 3G systems.[10] However, international frequency band coordination proves difficult, viz., only in 2000 is 3G service provision designated to three frequency bands (Gruber, 2005: 225). [11] National governments assign network operators to the pre-determined frequencies. Methods used by NRAs to assign spectrum licenses include: beauty contests; auctions; lotteries; and first-come-first-served methods. The first-come-first-serve mode dominated initial claims for electromagnetic spectrum for the delivery of commercial broadcasting and military services. The method however does not ensure that licenses are assigned to the bidder with the highest spectrum valuation. Lotteries are an alternative process whereby assignments are made randomly to applicants. Also, lottery processes do not guarantee efficient allocation.[12] More recently, beauty contests are widely employed in Asia and Europe to assign spectrum, whereby applications are rated by proposed service deployment characteristics, and social impact. Hazlett (1998) argues that beauty contests are inherently politically compromised and socially wasteful; while Cartelier (2003) notes that the possibility of NRAs being ‘captured’ is higher in beauty contests than other procedures because of asymmetric information and lobbying. [13]

Herzel (1951) proposed auctioning TV licenses as a way to let the market determine the color TV standard. Later, Coase (1959) developed the entire property rights approach to spectrum assignment. Legislation granting NRAs authority to auction spectrum first occurred in New Zealand (1989), followed by the UK (1990) and the US (1993). Auctions award spectrum based on bids received. As assignments are based on spectrum bid prices, they are regarded as efficient assignment models that are less susceptible to lobbying behavior and information asymmetry (Vickrey, 1961; Cramton, 2002: 606; Cartelier, 2003).[14] However, Vickrey’s (1961) revenue equivalence theorem requires independent

[10] The WRC in 1992 is principally used to allocate spectrum for 2G services, however, a small part of the spectrum was set aside for 3G services (Gruber, 2005: 231).

[11] This is due in part to much of the proposed frequency bands in the US allocated to 2G systems and the military (Gruber, 2005: 225).

[12] For this reason auctions replaced lotteries in the US in 1993 (McMillan, 1995).

[13] Regulatory capture occurs where the regulator acts in the interest of the firms rather than society.

[14] However, constant market evolution means the risk of winner’s curse is pervasive in spectrum auctions (Cartelier, 2003).

private spectrum valuations and risk neutrality across bidders. In practice these assumptions are unlikely to hold. Accordingly, careful NRA auction design is required to ensure efficiency and revenue maximization are achieved. Thus, NRA auction designs potentially impact on realized spectrum winning bids.

3. Factors affecting MNO Spectrum Valuations

The fundamental motivation for MNOs to acquire spectrum is to enable the provision of wireless services for profit (Klemperer, 2002a). When a firm assesses an opportunity to acquire spectrum offered for licence by an NRA, the ultimate consideration is whether it is in the operator's best interest to do so, viz., is spectrum purchase profitable? An MNO (Operator j) assesses this opportunity based on the conditions $r_{ij} - b_{ij} > 0$, where r_{ij} is the projected net revenue from use of spectrum package i by Operator j (based on spectrum award conditions, and operating revenue and cost estimates) through the licence period and b_{ij} is the final spectrum bid price made by the operator for the spectrum resource. Further, the quantity $b_{ij} - b_{ij}^{min} > 0$ is the bid premium an operator offers to obtain the spectrum licence, i.e., the excess above the reserve bid price (b_i^{min}) required by the NRA in the tender document. Premiums mostly arise when the process is competitive.[15] That is, the award value must not only exceed the minimum required spectrum bid price but be the largest value among all bidders. The spectrum assignment is efficient when the bid price accurately reflects the underlying opportunity costs of the firm.[16] When $r_{ij} - b_{ij}^{min} < 0$ then no bid is made as the operator incurs losses in providing 3G service over the spectrum. Therefore, from the published spectrum awards, data observable to the analyst is the winner's bid price, b_{ij}^*. When there is no bid (and hence no winner) or the winning bid just equals the reserve price then b_{ij}^* is censored at a zero value.

Factors that potentially impact on the winning spectrum bid price that are identified by the literature include spectrum package attributes. Attributes considered in the analysis are: the award date (Klemperer, 2002a), licence duration (Klemperer, 2002a), whether the package is revised (re-offered; Klemperer, 2002a), whether an entrant must be awarded a licence (Klemperer, 2002a), and the magnitude of the required minimum bid (reserve) price (Burguet and Sakovics, 1996; Klemperer, 2002a). Variables that describe the licence award process include the size of the upfront deposit (Hazlett, 2001) and the competitiveness of the process (Klemperer, 2002b). Additionally, operator post-award financial and network performance obligations can impact on the award spectrum bid price. A financial performance obligation variable considered is annual license fees (Bauer, 2003), while network performance obligation variables included are infrastructure sharing, and population coverage and timing (Klemperer, 2002b). Finally, exogenous variables that reflect national economic and mobile market conditions, respectively, are national income (Börgers and Dustmann, 2003) and population density (Klemperer, 2002b), and the competitiveness of domestic mobile telephony markets (Klemperer, 2002a). Whether Asian market spectrum winning bids are distinct is also considered.[17]

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15 Examples include auctions held in the United Kingdom (2000), Germany (2000), the Netherlands (2000), New Zealand (2001), Denmark (2001), Taiwan (2002), Indonesia (2006) and Estonia (2007). A winning bid may reflect an accurate assessment of the profitability of spectrum under the advertised award conditions or an error in judgement by the operator. For instance, the winning bid could be the result of the 'winner's curse' whereby the winning bid may be the result of a naïve bidder's largest positive error (Gruber, 2002: 66; Scanlan, 2001: 695).

16 Standard auctions (at best) ensure that the bidder with the highest private value wins, rather than the highest social value. Private and social values diverge as the winners compete in a marketplace (Cramton, 2002: 608).

17 Spectrum lot size and license availability are implicitly controlled for in the regression equation. In particular, the dependent variable (WBID) is adjusted for the amount of spectrum in each license. Namely, the winning bid is US$m per MHz per million population. The number of licenses up for auction enters via the competition variable ACOMP. Namely, ACOMP = Licenses/Bidders. Additionally, an anonymous referee has pointed out that the availability of substitutable spectrum now and in the future is likely to affect spectrum valuations.

4. Data and Variables

For the purpose of econometric estimation these data are drawn from the DotEcon Spectrum Awards database. Table 2 lists sample 3G spectrum auctions comprising the data set for the period 2000–2007. Importantly, these data are comprised of 23 cases (national spectrum awards), which does not equal the number of observations. That is, the 83 observations (individual national spectrum licenses tendered for auction) are mostly multiple-licence national auctions.[18] Namely, several national licenses are on offer simultaneously, and accordingly in a well designed auction it would be expected that equivalent licenses would sell for equivalent prices. That is, national auction winning bids are not truly independent of other winning licence bid values. The resulting compressed bid value range in part reflects common underlying macroeconomic and market conditions, and other strategic information available to bidders. Further, and perhaps more importantly, this limited winning bid value range also reflects different information sets available to operators (e.g., incumbents and entrants) and uncertainty about rival bidder behavior. However, while the precision of individual estimates may be more difficult to ascertain, they remain unbiased and consistent.

Table 2. 3G Spectrum Auctions, 2000–07

Country	Auction Commenced	Licenses Offered	Licence Awarded
United Kingdom	April 2000	5	5
Germany	June 2000	6	6
Netherlands	July 2000	5	5
Italy	October 2000	5	5
Austria	November 2000	6	6
Switzerland	December 2000	4	4
New Zealand	January 2001	4	4
Belgium	March 2001	4	3
Singapore	April 2001	4	3
Greece	July 2001	4	3
Denmark	September 2001	4	4
Czech Republic	December 2001	4	2
Israel	December 2001	5	3
Taiwan	February 2002	5	5
Norway	September 2003	1	1
Bulgaria	March 2005	3	3
Latvia	April 2005	1	1
Denmark	December 2005	1	1
Georgia	May 2006	3	3
Indonesia	February 2006	3	3
Estonia	January 2007	1	1
Nigeria	March 2007	4	4
Norway	December 2007	1	1
Total		**83**	**76**

Source: DotEcon Spectrum Awards database coverage.

Table 2 shows that it is only between March and December 2001 that licenses are not awarded. Accordingly, the auctions in Table 2 are separated into ‘regimes’ to test whether relatively high reserve prices from Regime One continue into Regime Two (when spectrum valuations are lower). Whilst Table 3 shows that reserve prices fall across each regime, this difference is only statistically

[18] The exception of auctioning a single licence occurs only in five cases (Norway 2003, Latvia 2005, Denmark 2005, Norway 2007 and Estonia 2007).

significant across Regime Two and Regime Three.[19] Therefore, licenses may go unsold in 2001 due to legacy RESERVE levels remaining constant while valuations fall.

Table 3. 3G Spectrum Auctions by Winning Bid and Reserve Price

Country	Auction Commenced	Mean Winning Bid	Mean Reserve Price
Regime One			
United Kingdom	April 2000	4.21	0.09
Germany	June 2000	3.87	0.06
Netherlands	July 2000	1.08	0.09
Italy	October 2000	1.39	1.12
Austria	November 2000	0.57	0.51
Switzerland	December 2000	0.12	0.12
New Zealand	January 2001	0.05	0.04
Average		*1.73*	*0.30*
Standard Deviation		*1.66*	*0.38*
Regime Two			
Belgium	March 2001	0.29	0.00
Singapore	April 2001	0.29	0.39
Greece	July 2001	0.28	0.38
Denmark	September 2001	0.63	0.00
Czech Republic	December 2001	0.11	0.21
Israel	December 2001	0.13	0.22
Average		*0.28*	*0.20*
Standard Deviation		*0.22*	*0.16*
Regime Three			
Taiwan	February 2002	0.37	0.25
Norway	September 2003	0.06	0.00
Bulgaria	March 2005	0.25	0.24
Latvia	April 2005	0.12	0.02
Denmark	December 2005	0.44	0.36
Georgia	May 2006	0.08	0.03
Indonesia	February 2006	0.02	0.00
Estonia	January 2007	0.13	0.12
Nigeria	March 2007	0.03	0.03
Norway	December 2007	0.05	0.00
Average		*0.17*	*0.12*
Standard Deviation		*0.15*	*0.12*

Source: DotEcon Spectrum Awards database coverage; *Note*: Mean winning bid and mean reserve price are US$m MHz per million population.

[19] An *F*-statistic for different variances across Regime One and Regime Two (6.75 with 34 and 51 degrees of freedom) exceeds the critical value (1.66). Therefore, the Null hypothesis that the variances are equal is rejected. Accordingly, a test for difference-in-means is conducted which accounts for different variance across regimes. The *t*-statistic of 1.48 (41 degrees of freedom) does not exceed the critical value (2.02 for a 5% significance level in a two-tailed test). Therefore, the Null hypothesis that the mean RESERVE from Regime One and Regime Two are equivalent is not rejected. Furthermore, an F-statistic for different variances across Regime Two and Regime Three (37.14 with 24 and 22 degrees of freedom) exceeds the critical value (2.03). Therefore, the Null hypothesis that the variances are equal is rejected. Accordingly, a test for difference-in-means is conducted which accounts for different variance across regimes. The *t*-statistic of 2.58 (26 degrees of freedom) exceeds the critical value (2.06). Therefore, the Null hypothesis that the mean RESERVE from Regime Two and Regime Three are equivalent is rejected.

Table 4 and Table 5, respectively, present mean, standard deviation and definitions for the dependent and independent variables used in the regressions based on national 3G spectrum awards. While valuations are converted to United States dollars (US$), categorical (1, 2, 3 …) variables are transformed into binary (dummy) variables, e.g., when an entrant must be awarded at least one licence: ENTRANT is set equal to unity, and zero otherwise. In Table 4 the dependent variable to be analyzed is WBID (winning bid amount). The variable is typically considered by economists to reflect the value of the spectrum package to the winning operator. In particular, higher revenues can arise from product market extension to 3G spectrum, thus adding revenue streams otherwise not feasible from current activities. Synergistic benefits also arise from lower costs (e.g., savings may occur through improved productivity or network economies).[20] Either source of benefits may flow through to profit.

Table 4. 3G Auction Dependent Variable Summary Statistics, 2000–07

Variable	Definition	Mean	Std Dev.
WBID	= Winning bid value (US$m per MHz per million population); = 0, otherwise	0.66	1.34

Figure 1 depicts 3G sample mean values for the auction reserve bid price (set by NRAs) and winning bid price (made by successful MNOs). Figure 1 demonstrates a decline in both the reserve and winning bid prices, and a narrowing of the margin between the winning bid and reserve prices. Such narrowing can result from several sources including learning-by-doing (e.g., from bidding experience) or an improved appreciation of the true worth of 3G business models and markets, both in the near and long term.

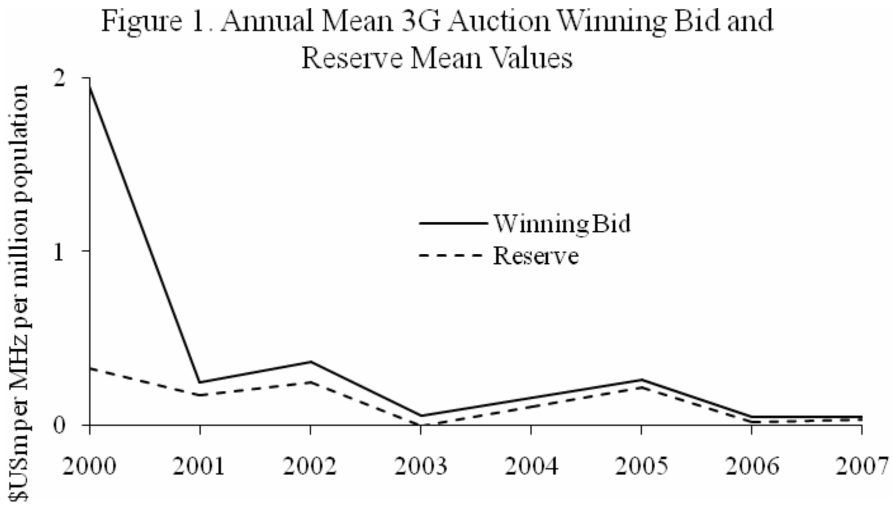
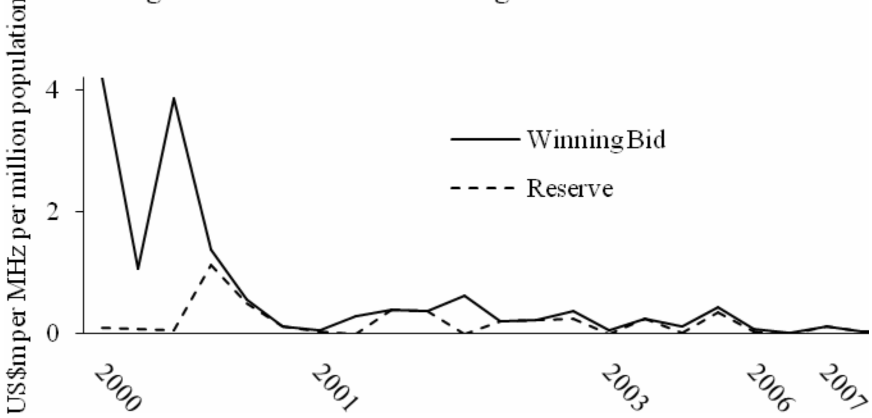


Figure 2 illustrates that similar patterns are also apparent for individual winning bid activity (rather than just for annual mean winning bid activity). That is, the phenomena of declining price (measured in US$m per MHz per million population), and bid-reserve price spread narrowing holds for individual auction winning bid activity. Further, the observed winning bid price volatility (across auctions) illustrated by Figure 2 suggests that individual country factors are important in explaining

[20] The spectral efficiency is the number of bits that can be sent per second over a channel of a given bandwidth (Gruber, 2001: 62).

winning bid price levels and the bid-reserve price spread. Accordingly, Table 5 lists variables (with definitions and sample summary statistics) that potentially explain such price movements.

Figure 2. 3G Auction Winning Bid and Reserve Values



The variables contained in Table 5 identify: national economic and mobile market conditions (winning spectrum prices, Asian country), spectrum package attributes (award duration, revised offering, entrant priority, minimum spectrum bid price), licence award process (minimum deposit), and operator financial (annual license fees) and network (infrastructure sharing, population coverage) post-award obligations.

Table 5. 3G Auction Independent Variable Summary Statistics, 2000–07

Variable	Definition	Mean	Std Dev.
National Economic and Mobile Market conditions			
AINITIAL[a]	= Average winning bid price (US$m)	1210.63	2507.65
ASIA	= 1, if Indonesia, Singapore or Taiwan; = 0, otherwise	0.14	0.35
Spectrum package attributes			
DURATION	= License term (years)	17.81	2.97
REVISED	= 1, if package is a re-offered licence; = 0, otherwise	0.10	0.30
ENTRANT	= 1, if at least one licence must be awarded to entrant; = 0, otherwise	0.14	0.35
RESERVE	= Minimum bid price (US$m per MHz per million population)	180.36	439.64
Licence award process			
DEPOSIT	= Initial deposit required (US$m)	10.48	22.75
Post-award financial performance obligations			
ANNUAL	= Mean annual licence fee (US$m)	2.31	0.77
Post-award network performance obligations			
SHARE	= 1, if infrastructure sharing is a licence requirement; = 0, otherwise	0.35	0.48
COVER	= Population that must be covered by the network (percent)	0.55	0.31
TIME	= Time to achieve required network coverage (years)	4.18	2.26

Note: (a) For country *i* AINITIAL is average winning bid price for other nations in period *t*. That is, $\sum_{j=1}^{n} b_{jt} n, \quad j \neq i.$

5. Initial Data Analysis

Prior to model estimation, national 3G award sample descriptive statistics are calculated. In particular, Table 6 through Table 9 list sample mean and standard deviation values for national auction and administrative (beauty contest and award) processes.[21] Table 6 and Table 7 concern 3G auction sample statistics for periods 2000–01 and 2002–07, respectively. Table 8 and Table 9 contain 3G administrative process sample statistics for the periods 2000–01 and 2002–07, respectively. Together these data suggest that the winning bids are different in character and magnitude by 3G spectrum

[21] Countries that used awards to issue 3G spectrum licenses include Poland (2000), Liechtenstein (2000), Latvia (2000), the Czech Republic (2001), Egypt (2001) and Slovenia (2001). The average winning 'bid' from these awards is US$0.434m per MHz per million population.

allocation process. In particular, the realized upper bound (maximum value) of spectrum winning bid is higher for auction processes for 2000–01, viz., US$5.48m (auction) compared to US$2.06m (administrative process), with the situation reversed in 2002–07, with mean realized winning bids for auctions and administrative processes at US$0.44m and US$0.93m, respectively. However, the mean WBID value is larger for auctions in both periods, i.e., US$1.13m (2000–01) and US$0.17m (2002–07) compared to US$0.34m (2000–01) and US$0.11m (2002–07), respectively. Finally, Table 6 through Table 9 also list the estimated slope coefficients for ACOMP (available licenses to bidders ratio), DURATION (licence term in years) and INCOME (GDP per capita) obtained from simple regressions on WBID. The coefficient estimates further suggest that the underlying process by which the spectrum bid values are determined is distinct. That is, for the auction regressions the estimated coefficients are opposite in sign to those reported in the administrative process regressions. Interestingly, Table 6 through Table 9 further suggests that a structural break occurred for both spectrum allocation processes after 2001. That is, the mean winning bid falls substantially from US$1.13m (2000–01) to US$0.17m (2002–07), while the corresponding values for the administrative processes are US$0.34m (2000–01) and US$0.11m (2002–07), respectively.

As a group, the findings reported in this section suggest modeling the behavior of 3G auction spectrum winning bids requires the specification and estimation of censored regression models. Additionally, any such modeling must consider the structural break in the sample data between the periods 2000–01 and 2002–07. Accordingly, the approach employed below is to concentrate on the auction sample and estimate a censored regression incorporating a dummy variable to allow for a downward level shift in WBID values after 2000–01.[22]

Table 6. Selected 3G Auction Sample Statistics, 2000–01

Variable	Minimum	Maximum	Mean	Standard Dev.	Coefficient
WBID	0.00	5.58	1.13	1.46	–
ACOMP	0.38	2.00	1.07	0.42	–1.99873***
DENSITY	14.38	6745.76	641.29	1649.34	–0.00004
INCOME	6077.5	34802.0	21452.8	6918.5	–0.00000

Notes: no. obs = 55; *** significant at 1%.

Table 7. Selected 3G Auction Sample Statistics, 2002–07

Variable	Minimum	Maximum	Mean	Standard Dev.	Coefficient
WBID	0.01	0.44	0.17	0.15	–
ACOMP	0.25	1.00	0.78	0.22	–0.13788
DENSITY	14.77	698.95	221.92	260.60	0.00039***
INCOME	1160.8	83484.8	12799.4	20377.0	0.00000

Notes: no. obs = 25; *** significant at 1%.

[22] This variable is included in Stage One of estimation.

Table 8. Selected 3G Administrative Process Sample Statistics, 2000–01

Variable	Minimum	Maximum	Mean	Standard Dev.	Coefficient
WBID	0.00	2.06	0.34	0.54	–
ACOMP	0.40	3.00	1.01	0.57	0.68809***
DENSITY	13.87	483.46	128.89	147.02	0.00012
INCOME	4453.8	36811.0	20835.5	10705.8	–0.00000

Notes: no. obs = 32; administrative award is lottery, beauty contest or hybrid process; *** significant at 1%.

Table 9. Selected 3G Administrative Process Sample Statistics, 2002–07

Variable	Minimum	Maximum	Mean	Standard Dev.	Coefficient
WBID	0.00	0.93	0.11	0.16	–
ACOMP	0.20	2.00	1.08	0.47	0.01601
DENSITY	8.41	294.66	107.42	84.76	–0.00055*
INCOME	1159.2	64403.8	15272.8	16852.5	0.00000

Notes: no. obs = 45; administrative award is lottery, beauty contest or hybrid process; * significant at 10%.

6. Regression Model Specification

A censored regression model is estimated to obtain estimates of the impact of NRA controlled variables on winning national WBID values. However, with the average winning bid price (AINITIAL) included as an argument in the WBID estimating equation, simultaneity bias may be introduced. In particular, a rise in AINITIAL may increase national WBID values, and vice versa. Consequently, estimates of the effect of AINITIAL on WBID are potentially understated. To avoid the problem Two Stage Least Squares (2SLS) Instrumental Variable (IV) techniques are applied. The Stage One estimation requires that IVs correlated with AINITIAL and exogenous to WBID are regressed on AINITIAL. Predicted values from this regression (PAINITIAL) are substituted for AINITIAL in the Stage Two regression on WBID. The independent variables included in the Stage One regression are the national and mobile market condition variables contained in Table 10 below.[23]

Table 10. 3G Auction National and Mobile Market Variable Summary Statistics, 2000–07

Variable	Definition	Mean	Std Dev.
ACOMP	= Available licenses to bidders (ratio)	0.99	0.39
DENSITY	= National population per square kilometer (persons)	525.08	1418.16
INCOME	= GDP per capita (US$ thousands)	19054.89	12689.53
SHIFT	= 1, if auction was held in 2000–2001; = 0, otherwise	0.72	0.45

[23] A Hausman test (1978) for the endogeneity of AINITIAL is conducted. Namely, WBID is regressed on Table 5 arguments (including AINITAL, the potentially endogenous variable) and the Stage One residuals. The p-value for the residuals (0.00) rejects the Null Hypothesis that the error term is uncorrelated with AINITIAL. That is, the concern regarding simultaneity is justified.

These mobile market (ACOMP, DENSITY) and national economic (INCOME, SHIFT) variables are selected as instruments as they are assumed correlated with AINITIAL but exogenous to WBID. For example, higher per capita national income is positively correlated with MNO licence valuations via potential market size (which is associated with an ability to charge higher service prices). Also, higher population densities enhance licence values through achievable scale economies. Additionally, more competitive auction processes are positively correlated with winning spectrum bid prices. Finally, observed post-2001 realized spectrum prices are lower, perhaps reflecting learning effects.

The Stage Two estimation recognizes the censored nature of WBID data.[24] In particular, dependent variable WBID is censored as only winning bid values greater than the reserve bid price are observed. That is, the observed price must not only be the largest value among all bidders, but must also exceed the NRA specified minimum spectrum bid price. When the maximum bid (based on operator valuation) does not exceed the minimum spectrum bid price then the associated ‘observed’ price is zero. The regression model based on the preceding discussion is referred to as the censored regression (or Tobit) model. The regression is obtained by making the mean of the censored model correspond to a classical regression model. The general formulation is usually given in terms of an index function,

$$y_{ij}^{*} = x'\beta_{ij} + \varepsilon_{ij},$$
$$y_{ij} = 0 \;\text{ if }\; y_{ij}^{*} \le 0,$$
$$y_{ij} = y_{ij}^{*} \;\text{ if }\; y_{ij}^{*} > 0,$$

where $x_i = (1, x_{i1}, ..., x_{ip})'$ is a vector of p covariates which affect Spectrum Package i valuations and $\beta_j = (\beta_{j0}, \beta_{j1}, ..., \beta_{jp})'$ is a corresponding vector of parameters to be estimated. The stochastic component ε_{ij}, consists of unobserved factors that explain the marginal spectrum valuations of Operator j. Each ε_{ij} is drawn from a J-variate Normal distribution with zero conditional mean and variance, where $\varepsilon \sim N(0, \Sigma)$. For a randomly-drawn observation from the population, which may or may not be censored,

$$\mathrm{E}[\mathrm{y_{ij}} | \mathrm{x_{ij}}] = \Phi\left(\frac{\mathrm{x}_{ij}'\beta}{\sigma}\right)(\mathrm{x}_{ij}'\beta + \sigma\lambda_{ij}),$$

where

$$\lambda_{ij} = \frac{\phi[(0 - \mathrm{x}_{ij}'\beta)/\sigma]}{1 - \Phi[(0 - \mathrm{x}_{ij}'\beta)/\sigma]} = \frac{\phi[\mathrm{x}_{ij}'\beta)/\sigma]}{\Phi[(\mathrm{x}_{ij}'\beta)/\sigma]}.$$

For the case with censoring at zero and normally distributed disturbances, the marginal effects in the censored regression model, are:

$$\frac{\partial E[y_{ij} | x_{ij}]}{\partial x_{ij}} = \beta\Phi\left(\frac{x_{ij}'\beta}{\sigma}\right).$$

The log-likelihood function for the censored regression model is:

$$\mathrm{Ln(L)} = \sum_{y_{ij}>0} -\tfrac{1}{2}\left[\ln(2\pi) + \ln\sigma^2 + \frac{(y_{ij} - x_{ij}'\beta)^2}{\sigma^2}\right] + \sum_{y_{ij}=0} \ln\left[1 - \Phi\left(\frac{x_{ij}'\beta}{\sigma}\right)\right].$$

[24] Maddala (1983) considers censored values occur when variables are limited in their range because of some underlying stochastic choice mechanism (e.g., data on consumer durable expenditures). This contrasts truncated observations that are incomplete due to a selection process in the design of the study (e.g., negative income tax experiment data). Thus, truncation changes the sample size while censoring does not.

Finally, the estimated coefficients are comprised of both the impact of changes in the observed WBID and the probability any bid is a winning WBID value (McDonald and Moffitt, 1980). For coefficient values above the limit the marginal effects is scaled for the probability that the latent variable is observed.[25] Limdep calculates the conditional mean of the model at the mean of the independent variables to scale the coefficients.

7. Estimation

Estimation is via Limdep version 9.0. Stage One parameter estimates are listed in Table 11. The reported F-Statistic exceeds ten and indicates that the instruments are suitable, a necessary condition for an unbiased 2SLS estimator (Stock and Watson, 2002: 350). The Stage Two censored regression model estimates reported in Table 12 indicate a significant Lagrange Multiplier test of model restrictions. Also, ANOVA (22%) and DECOMP (35%) fit measures show improvement in the log-likelihood relative to the restricted model.

Table 11. Stage One Estimates

Variable	Coefficient
INCOME	0.04469** (2.239)
DENSITY	-0.26755 (-1.394)
ACOMP	-1295.3** (-2.570)
SHIFT	3255.9*** (4.882)
n	83
F–Statistic	10.59

Notes: *t* statistics in parentheses. ** significant at 5%; *** significant at 1%.

[25] Limdep provides a scale factor, analogous to the sample proportion of observations above the limit, to compute the marginal effects of the independent variables (Greene, 2008).

Table 12. Censored Regression Estimates

Category	Variable	Coefficient	Marginal Effect
	Constant	0.09253* (0.165)	0.07420 (0.132)
National economic and mobile market conditions	PAINITIAL[a]	0.00018*** (5.517)	0.00014*** (4.427)
	ASIA	0.45885*** (4.269)	0.36794*** (3.425)
Spectrum package attributes	DURATION	–0.04482 (–1.392)	–0.03594 (–1.116)
	REVISED	0.59205*** (4.072)	0.47474*** (3.267)
	ENTRANT	–0.23286 (–1.471)	–0.18672 (–1.180)
	RESERVE	1.28515*** (5.077)	1.03052*** (4.074)
Licence award process	DEPOSIT	0.01299* (1.680)	0.01041 (1.348)
Financial obligations	ANNUAL	–0.00718*** (–13.681)	–0.00576*** (–10.959)
Network obligations	SHARE	1.25271*** (2.710)	1.00450** (2.174)
	COVER	–1.69090*** (–6.237)	–1.35588*** (–5.004)
	TIME	0.31871*** (9.807)	0.25557*** (7.857)
	n	83	
	ANOVA	0.220765	
	DECOMP	0.350991	
	Log likelihood	–108.9118	

Notes: (a) PAINITIAL is predicted AINITIAL values. *t* statistics in parentheses. * significant at 10%; ** significant at 5%; *** significant at 1%. Standard errors are adjusted for heteroskedasticity.

Further, Table 13 demonstrates that the estimated model predicted values track well for 2000–2007 (0.00 Absolute Average Deviation). However, the model performs less well for the sub-period 2002–2007 (0.03 Absolute Average Deviation). Finally, Table 14 reports joint significance tests for the explanatory variable categories: national economic and mobile market conditions; spectrum package attributes; and network obligations. The tests reject the null hypotheses that the variable groupings are insignificant.

Table 13. 3G Auction Predicted and Actual Mean Winning Bid Values, 2000–07

Period / Region	Actual	Predicted	Absolute Average Deviation
2000–01	1.13	1.12	0.01
2002–07	0.17	0.20	0.03
2000–07	0.86	0.86	0.00
Africa	0.03	0.10	0.07
Australasia	0.20	0.20	0.00
Europe	1.16	1.17	0.01
Middle East	0.13	0.00	0.13

Note: Winning bids are US$m per MHz per million population.

Table 14. Joint Significance Tests

Category	Variable	Wald statistic
National economic and mobile market conditions	PAINITIAL ASIA	14.08***
Spectrum package attributes	DURATION REVISED ENTRANT RESERVE	21.15***
Network obligations	SHARE COVER TIME	33.97***

Notes: *** significant at 1%. The above categories are tested as they contain several variables.

Turning to the impact of the explanatory variables on the 3G winning bid value (WBID) several distinct patterns emerge from examining Table 12. First, national economic and mobile market condition variables are individually significant in explaining winning bid behavior. In particular, higher winning bids occur when current prices are high (PAINITIAL = 0.00014) and for Asian countries (ASIA = 0.36794). For variables describing spectrum package attributes, revised licenses (REVISED = 0.47474) and reserve bid price (RESERVE = 1.03052) have positive impacts. Importantly, reserve prices are specified by the NRA in the tender document. Table 12 also indicates that post-award financial obligations imposed by NRAs are important in the decision calculus applied by MNOs in their bidding. For instance, winning bid values are less likely to increase with higher post-award payment obligations (ANNUAL = –0.00576). Finally, of the network obligations imposed on operators, infrastructure sharing (SHARE = 1.00450) has a positive independent impact on WBID values. Additionally, the portion of the population which must be covered by the license (COVER = –1.35588) has a negative impact on winning bid while the estimated TIME (time to achieve required network coverage post award) coefficient of 0.25557 suggests that operators view these obligations as binding on their post-award behavior.

Finally, Table 15 contains elasticity estimates for policy relevant (under NRA control) variables. Elasticity values that are either elastic (or near elastic) have a more important impact on operator auction bidding behavior. The COVERAGE (portion of the population which must be covered by the license) elasticity value (evaluated at the sample mean of the independent variables) suggests that when the coverage requirement increases by 1% above the mean there is a 0.86% fall in WBID value (reduction in the perceived value of the licence to the winning bidder). Finally, the TIME (time to achieve NRA specified network geographic coverage obligations) is perceived as binding by operators. Importantly, the more distant is the assessment of achieving these objectives the greater is the realized winning bid. The absolute values of the estimated elasticities for REVISED, RESERVE, ANNUAL and SHARE are less than 0.5 in magnitude. That is, the higher the reservation price (RESERVE), the higher the winning bid; the higher the annual payment (ANNUAL), the lower the winning bid; and the incidence of a re-offered license (REVISED) or infrastructure sharing obligation (SHARE), the higher the winning bid.

Table 15. NRA Control Variable Elasticity Estimates

Category	Variable	Elasticity
Spectrum package attributes	DURATION	–0.74
	REVISED	**0.05**
	ENTRANT	–0.03
	RESERVE	**0.26**
Licence award process	DEPOSIT	0.13
Financial obligations	ANNUAL	**–0.15**
Network obligations	SHARE	**0.41**
	COVER	**–0.86**
	TIME	**1.24**

Note: Bold indicates coefficient is significant

8. Conclusions

During the past decade there has been considerable published research examining auction behavior. The studies are primarily focused, presumably due to the data available, on the optimal design of auctions and their performance. Indicators of auction ‘success’ are typically some measure of participation (more is better), an absence of collusive bidding behavior and that winning prices accurately reflect, more or less well, the ‘true’ value of the spectrum to winning bidders (that the auction is efficient). Questions that are not adequately addressed by this theoretical approach are the relative (quantitative) importance of particular aspects of an auction’s design to the achievement of desired outcomes. Accordingly, the modeling approach employed in this study is based on the premise that the form of an instrument matters for 3G auctions, and that NRAs have an opportunity through this design to achieve desired goals. In particular, this study addresses the questions: What is the relative importance of ‘macro’ (environmental) variables, *viz á viz*, NRA choice (auction design) variables on auction outcomes? In what type of auction design (magnitude) are NRA-specified auction designs likely to succeed? What can be said about the relationship between post-auction award obligations and spectrum valuations?

The short answer to these questions (in the context of this sample) is that less binding (far term) post-award coverage obligations enhance spectrum value, and not surprisingly, that when the initial value is close to the ‘true’ operator value of the spectrum then the winning bid is higher as the 'winner's curse' risk is diminished. A limitation of the analysis is that the sampling frame only allows consideration of national 3G spectrum licence bidding activity. A more thorough analysis would consider the impact on 'regional' auction bidding.

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