

Ihle, Hans-Martin; Marsden, Richard; Traber, Peter

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Does the choice of auction format affect prices in spectrum auctions?



By **Hans-Martin Ihle,**
Richard Marsden,
and
Peter Traber

Auctions are now the standard approach for allocating spectrum licences for mobile use worldwide. The types of auction format used to award spectrum vary widely, including both sealed bids and open formats, such as the Simultaneous Multiple Round Auction (SMRA), clock auction (clock) and combinatorial clock auction (CCA). To a significant extent, spectrum awards have become a laboratory for testing new auction designs for simultaneous award of related products, with academic analysis of these formats lagging practice. Recent research into these formats has highlighted differences in the incentives they create for bidding behaviour by participants which may in turn lead to different pricing outcomes.

This paper investigates whether there is empirical evidence to support theoretical arguments that the choice of auction format affects price outcomes. The scope for such analysis has historically been constrained by the limited number of observations, with outcomes of individual spectrum auctions being highly sensitive to local factors. However, with the growth in the number of countries using auctions to allocate spectrum (often repeatedly and using different formats), it is now possible to identify reasonably robust sample sizes.

We find statistical evidence that open formats produce higher revenues than sealed bid formats. This is consistent with the theory that, in common-value settings, open formats allow for price discovery, which in turn encourages bidders to be confident in their willingness to express their valuations through bids, leading to more efficient (and higher-priced) auction outcomes. It is widely recognised that bidders for mobile spectrum typically have a high degree of common value in their valuations, given that they are typically competitors with closely related business cases.

We also find evidence that the CCA produces higher prices than other open formats. Interestingly, this effect is much more pronounced for low-band (sub-1 GHz) spectrum, which is scarcer than other types of mobile spectrum, and where the stakes for mobile operators are highest. This result is consistent with recent research which suggests that prices in CCAs may be distorted upwards by incentives for bidders to bid strategically to drive up rivals' prices.

1. Literature review

A key principle in auction theory is the revenue-equivalence theorem. First demonstrated by Vickrey (1961)¹, it shows that there is a close relationship between an efficient allocation and pricing. The theorem states that expected revenues are independent of the chosen mechanism provided that:

- bidders are risk neutral and have privately-known valuations independently drawn from a common strictly-increasing, atomless distribution; and
- the mechanism leads to an efficient allocation (i.e. the bidder with the highest valuation wins) and any bidder with the lowest valuation expects zero surplus.²

A critical condition for the theorem to hold is that valuations are independent of each other. This is closely linked to the issue of winner's curse.³ With common-value uncertainty, the winner of a sealed bid auction will know that he will have had the most optimistic estimate of the common value of the item it won and may have paid more than its actual realisable value. To avoid the winner's curse, bidders should bid less aggressively in a sealed bid auction which leads to lower revenues and potentially a less efficient outcome (when comparing the residual private value components) than is optimal. As Ausubel (2004) points out, "*when there is a common value component to valuation and when bidders' signals are affiliated, an open ascending bid format may induce participants to bid more aggressively (on average) than in a sealed bid format, since participants can infer greater information about their opponents' signals at the time they place their final bids.*"⁴

In spectrum auctions, four types of auction formats have been used most widely:

- **Sealed-bid auction.** In a sealed-bid auction, bidders only have one opportunity to submit bids. The auction may either be non-combinatorial, in which case bidders submit bids for individual lots or combinatorial, in which case bidders submit bids for packages. Once the auctioneer has received all bids, it determines the value-maximising allocation. Winning bidders either pay the amount of their bid (pay-as-bid rule), a second price (based on the highest losing bid) or a clearing price (based on the lowest winning bid).
- **Simultaneous multiple round auction (SMRA).** An SMRA is conducted over a series of rounds. In the first round, bidders submit bids for individual blocks. In some variants of the SMRA, bidders can only submit bids at predetermined prices in each round. In others, they can select a bid amount from a predetermined menu of prices. At the end of each round, the auctioneer determines the standing high bid for each block (the highest bid submitted) and a new price (or menu of prices) for each block. The auction continues until no more new bids are placed. The SMRA is usually run with activity rules which ensure that bidders reveal their demand from the beginning of the auction.
- **Clock auction.** In a clock auction, similar blocks are grouped into categories. In each round, bidders state their demand (in terms of the number of blocks) at current round prices. The price of a category is increased if the number of blocks demanded by all bidders exceeds the available supply. The auction continues until demand is equal to or less than supply in all categories. The clock auction is sometimes followed by a follow-up round in which any unsold blocks are offered. In other versions of the clock

auction, bidders submit exit bids when they reduce demand which may be used to allocate blocks that would otherwise go unsold.

- **Combinatorial clock auction (CCA).** The CCA is a multi-round package auction. It consists of a clock auction followed by a combinatorial sealed-bid round. In the latter, bidders may either raise their clock bids or submit bids for additional packages subject to constraints imposed by their bid decisions in the clock rounds. At the end of the sealed-bid stage, winning bids and prices are determined drawing on all bids submitted throughout the process, i.e., both clock round bids and sealed bids. The CCA is usually run with a second-price rule which determines prices based on how much other bidders were willing to pay for the packages won by a winner / group of winners.

Spectrum blocks in an auction may be complements, meaning that the value of a package of blocks is greater than the sum of the individual values. In this situation, an SMRA exposes bidders to aggregation risk. A bidder may wish to pursue the entire package, but by doing so risks driving the prices for the individual component blocks above their standalone valuations. If the sum of prices exceeds the bidder's valuation for the package, it would stop bidding, but it may be left 'stranded' with standing high bids on a subset of the blocks at prices that exceed standalone valuations.

The standard clock auction is a package-bid format and protects bidders against aggregation risks, as bids from previous rounds are not maintained. Variants, such as the clock plus (adopted for the multiband auction in Singapore in 2017) or the clock format used for the Forward Auction in the US Incentive Auction (2017) have additional rules that prevent bidders from dropping demand under certain circumstances. This makes unsold lots less likely but at the expense of restricting bidder flexibility and exposing them to a degree of aggregation risk.

With the SMRA and clock variants, where aggregation risk exists, the impact on bidder behaviour and price outcomes is ambiguous.⁵ On the one hand, if a bidder deems it unlikely to win a larger package, the logical response is to bid conservatively based on standalone values. On the other hand, if it thinks it can win the larger package, it may be rational to bid above standalone values and, if necessary, even bid above the full value of a package if this offers higher surplus than falling back to a subset of spectrum blocks.

Ausubel, Cramton, Pycia, Rostek and Weretka (2014)⁶ show that in any ascending uniform or pay-as-bid auction, such as the SMRA and the clock auction, bidders may have an incentive to engage in strategic demand reduction. Bids for marginal blocks affect the price for other blocks. By reducing demand for marginal blocks before the price reaches their valuations, bidders may be able to secure a lower price on the other blocks they win. Strategic demand reduction, however, only has an impact on the efficiency of the allocation if bidders' expectation about the likelihood of winning certain amounts of spectrum is fundamentally wrong. Otherwise, it only affects the prices paid, but not the efficiency of the resulting allocation.

The aim of the CCA format was to develop a practical package-bid format that eliminates aggregation risk and encourages straightforward bidding (i.e. bidding according to valuations). On the first goal, the format is, by definition, effective. However, evidence suggests that the second goal has not been realised. While the format seems to be effective at removing incentives for demand reduction, it has been associated with strategic bidding, and with high price and highly asymmetric

price outcomes (Swiss multiband auction in 2012, Austrian multiband auction in 2013 and Dutch multiband auction in 2012).

Recent theoretical research shows that the CCA provides incentives for bidders to bid strategically to drive up rivals' prices. For example, Janssen and Karamychev (2013)⁷ demonstrate that if bidders have a primary preference for achieving a low price, and a secondary preference for raising their opponents' costs, they will bid aggressively in the clock rounds and submit spiteful bids in the sealed bid round. Janssen and Kasberger (2015)⁸ and Levin and Skrzypacz (2016)⁹ provide theoretical evidence suggesting that this may lead to highly inefficient equilibrium outcomes in the CCA. Marsden and Sorensen (2017)¹⁰ provide explanations as to why bidders in CCAs may bid strategically in ways that could inflate price outcomes rather than bid straightforwardly based on valuations. A recent econometric study by Koutroumpis and Cave (2017)¹¹ supports these observations as it finds that the CCA is associated with higher prices than other auction formats.

There is an ongoing debate in the academic community about the potential impact of high spectrum prices on consumer prices and network investment. Kwerel (2000)¹², Wolfstetter (2001)¹³ and Cambini and Garelli (2017)¹⁴, have argued that upfront spectrum fees are sunk costs and therefore do not have any negative impact. On the other hand, Marsden, Ihle and Traber (2017)¹⁵ provide theoretical and econometric evidence which links high spectrum prices to lower network investments and higher consumer prices. They argue that high spectrum prices could lead to hold up¹⁶, provide costly entry barriers¹⁷, and may put strain on the finances of mobile operators to the extent that they will reduce their investments (pecking-order theory¹⁸ and internal financing constraints¹⁹).

2. Motivation

The aim of this paper is two-fold:

- Determine if there is statistical evidence to support the supposition that bidders face common-value uncertainty in spectrum auctions. If this is the case, we would expect to observe higher prices, on average, in open auctions than in sealed-bid auctions.
- Extend the panel data model developed by Koutroumpis and Cave (2017) to not only estimate whether different auction formats systematically achieve different prices, but also whether the impact varies for different types of spectrum. In short, we augment the panel data model to estimate band-specific effects and their interaction with the choice of format.

We further address two limitations of the Koutroumpis and Cave (2017) model:

- It uses licence-level data. This means that auctions which include many licences (i.e. either regional awards, such as US awards with thousands of individual licences, or awards with many winners) carry more weight in the estimation than awards that only include a few licences. We will correct for this by only including a single price point for each band in each award.
- It only estimates whether different auction formats lead to higher prices relative to beauty contests and direct awards. The paper does not provide any evidence that the prices achieved by different auction formats are statistically different. Our extension measures whether some auction formats produce higher prices than others.

3. Data

We have gathered a dataset containing 213 spectrum auctions worldwide from 2007 to 2018.²⁰ For each auction, we determine a price per MHz/Pop for each band that was included in that auction.²¹ To make prices comparable, we make the following adjustments:

- **Annual fees.** When using auction prices, it is important to consider associated licence fees as well. In some jurisdictions, annual fees are relatively high which may depress prices in the auction. To get a better estimate of market prices, we add the net present value of these annual fees to auction prices.
- **Currency.** We convert all data points to US dollars using implied IMF purchasing power parity (PPP) rates. PPP rates take into account differences in income across different countries and are adjusted in a way so that an identical good in two different countries has the same price when expressed in the same currency.
- **Inflation.** We adjust all licence prices for inflation using US CPI.
- **Licence duration.** Licence durations differ across awards. To draw any meaningful comparisons, we normalise licence values using a discounted cash flow approach. In the following, we adjusted all licence prices for a reference licence duration of 15 years using a WACC of 8%.
- **Size of spectrum allocation and population covered.** We use prices per MHz per Pop throughout. This is a standard measure to adjust for the population covered and the size of the spectrum blocks sold.

A significant challenge when analysing data on spectrum auction outcomes is the importance of country-specific factors, such as the number and strength of incumbent mobile operators, the level of urbanisation or the regulatory framework. In our panel estimation, we attempt to account for such effects by including country-specific fixed effects to capture time-invariant factors. A possible limitation of our approach is that some of these local factors may vary between awards. Additionally, we have not considered the impact of reserve prices, which vary considerably across awards.

In recent years, there has been a huge increase in the number of awards worldwide using auctions, as well as increased use of different auction formats. Consequently, we now have a rich and diverse dataset of prices achieved by different formats which can be explored using sophisticated econometric techniques to investigate whether different formats achieve different prices. In our sample, we group spectrum awards into four categories based on the type of auction used: sealed bids; SMRAs; clock auctions; and CCAs.

We also identify three broad categories by mobile frequency band:

- **Low-band spectrum ("low").** This includes all sub-1 GHz bands designated for mobile use: 600 MHz, 700 MHz, 800 MHz, 850 MHz and 900 MHz. Low-band spectrum has excellent propagation, supporting greater geographic coverage and better in-building penetration relative to higher frequencies. As such, fewer base stations are needed to serve an area than with higher spectrum bands translating into lower deployment costs. As low-band spectrum is relatively scarce and in high demand for other uses, it typically commands a price premium over other bands.

- **Mid-band spectrum (“mid”).** This includes all mid-band capacity spectrum designated for mobile use: L-Band (1400/1500 MHz), 1800 MHz, 2100 MHz, AWS (1700/2100 MHz) and PCS (1800/1900 MHz). Some of this spectrum is still used to provide 2G and 3G mobile use, but increasingly it is being repurposed for 4G capacity. These bands are most commonly deployed in urban settings but are also used to provide extra capacity in rural settings.
- **Higher band spectrum (“high”).** These ‘higher’ frequency bands are still suitable for extending capacity on urban macrocells, but their weak propagation means they are generally unsuitable for coverage. These bands include 2300 MHz, 2600 MHz (FDD/TDD) and 3400 – 3800 MHz, all of which have been identified for 4G or 5G use. As there is more bandwidth available in these higher bands, this spectrum is less scarce and has historically sold at a discount compared to lower frequencies.

There are two important differences between our dataset and the one used by Koutroumpis and Cave (2017):

- We only consider awards since 2007, which corresponds to the “4G era” of mobile communications. We deliberately exclude data from the 3G era, as prices in some of these auctions were likely skewed upwards by bidder exuberance linked to the dotcom bubble in 2000, and downwards by the subsequent backlash in market sentiment. We suppose that auctions pre-2007 are less likely to provide meaningful information about the impact of different auction formats on prices.
- We focus exclusively on auctions. Prices set in beauty contests or direct awards are set administratively and not a function of valuations or competitive bidding. They therefore do not contain any information about the impact of the choice of auction format on bidding.
- We only use a single price point for each band awarded in an auction. This means each price point receives equal weight in the regression and the regression results are thus not skewed by either the number of licences awarded or the number of winning bidders.

Owing to these adaptations, the total number of observations in our dataset is smaller than the number of observations in the dataset used by Koutroumpis and Cave (2017).

The following figures provide a summary of the available data for each spectrum type. Across all three spectrum types, sealed bid auctions tend to achieve consistently lower revenues.²²

Figure 1 shows the pricing outcomes for “low” band spectrum. The three open formats (clock, SMRA, CCA) have produced a wide range of pricing outcomes for this type of spectrum:

- The higher priced SMRA and clock auctions are from Hong Kong, Taiwan, Singapore and Thailand.
- The higher priced CCAs are from the Netherlands, Canada, Ireland and Austria.
- A very competitive auction in Singapore in 2017 achieved the two highest-priced clock outcomes.

Figure 1: Price outcomes for "low" band (sub-1 GHz) spectrum by auction type

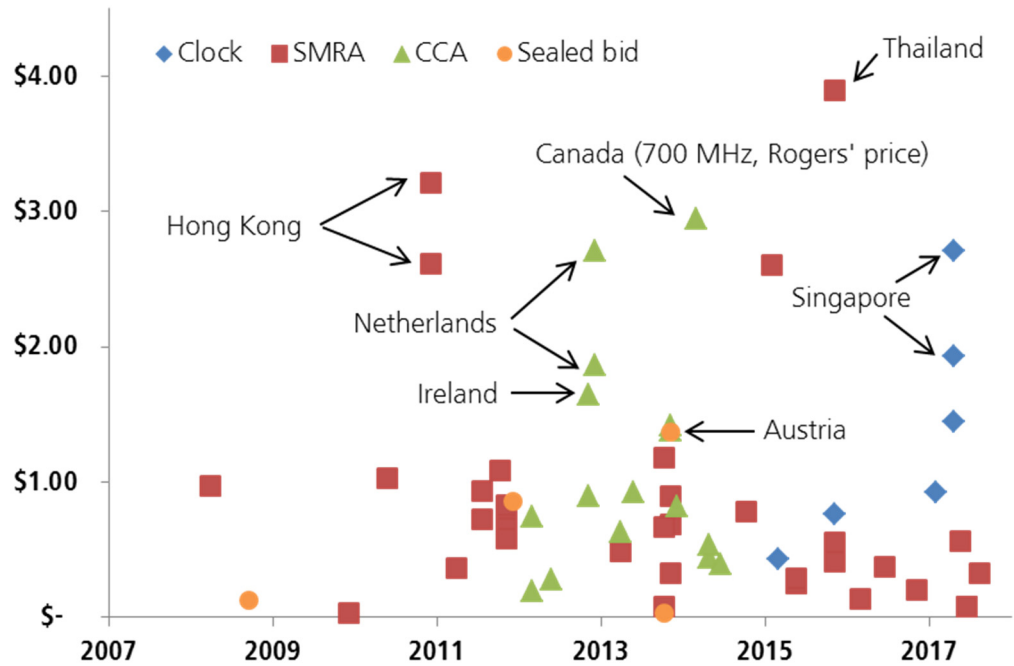


Figure 2 provides an overview of the pricing outcomes for "mid" band capacity spectrum. There does not appear to be a significant difference across the three open formats. Some competitive SMRAs in Taiwan, Canada and the US produced the highest-priced outcomes.

Figure 2: Price outcomes for "mid" band (1500 MHz – 2180 MHz) spectrum by auction type

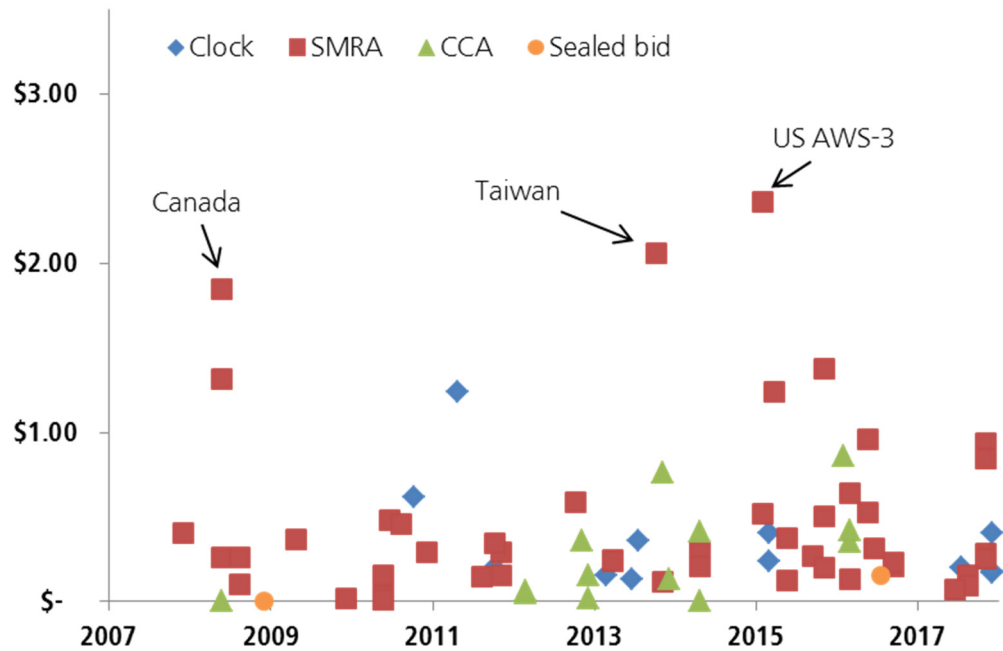
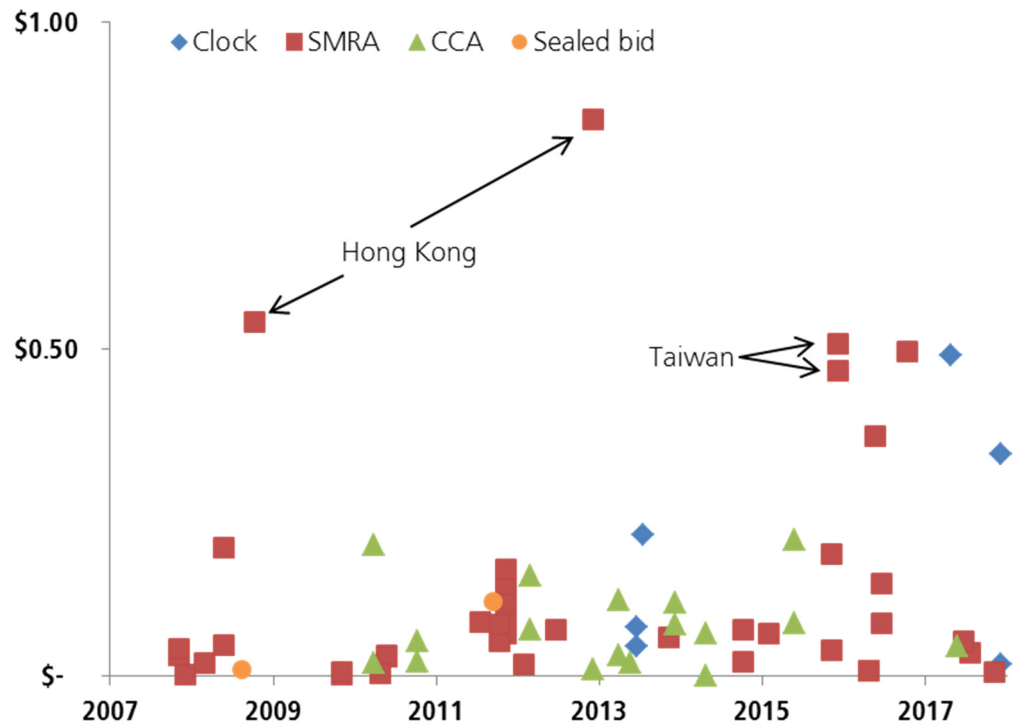


Figure 3 provides an overview of the pricing outcomes for “high” band spectrum. Again, competitive SMRAs in Hong Kong and Taiwan produced the highest-priced outcomes.

Figure 3: Price outcomes for “high” band (2.3 GHz – 3.8 GHz) spectrum by auction type



4. Open versus sealed-bid formats

To test our first hypothesis that open formats lead to consistently higher revenues, we estimate the following equation using OLS regression (with fixed effects):

$$\ln(p_{it}) = \sum_k D_{itk} + \sum_t y_t + \sum_c x_c$$

Where p_{it} is the band price in an auction and the dummy variables D_{itk} include all cross-product dummies for auction format (SMRA, clock, CCA) and spectrum band type (Sub-1, LM-CS, HM-CS). We also include a fixed effect for each year, y_t , and each country x_c .

The following table summarises the results of the regression.

Table 1: Open versus sealed-bid formats (regression results)

	Estimated coefficient
Low band	1.83 (0.45) ***
Low band & Clock	1.04 (0.59) *
Low band & SMRA	1.3 (0.45) ***
Low band & CCA	1.96 (0.5) ***
Mid band	0.21 (0.83)
Mid band& Clock	1.68 (0.67) **
Mid band& SMRA	2.22 (0.66) ***
Mid band& CCA	1.4 (0.84) *
High band& Clock	1.11 (0.83)
High band & SMRA	1.08 (0.59) *
High band & CCA	0.91 (0.64)
Year FE	Yes
Country FE	Yes
R-Squared	0.80
Observations	209

*Robust standard errors in parentheses. * 10% significance, ** 5% significance, *** 1% significance*

The baseline case is a sealed bid auction for “high” band spectrum. “Low” band spectrum generally sells at a premium, even in a sealed bid contest, whereas “mid” band spectrum does not.

The results in Table 1 show that all open formats produce significantly higher prices for both “low” band and “mid” band spectrum. The evidence is less clear for “high” band spectrum with only the SMRA producing higher prices than the sealed bid formats. However, the sample size in this case is small and the result may be driven by high-priced auctions in Hong Kong and Taiwan (see Figure 3) and thus may not be a general result.

Our observations are consistent with the hypothesis that price discovery is important for bidders in spectrum auctions as they are subject to common-value uncertainty. The results may imply that open formats allow them to bid more aggressively and lead to higher revenues and likely higher efficiency than sealed-bid formats.

5. Comparison of open formats

As Figures 1, 2 and 3 show, there have been a wide range of price outcomes for all three types of spectrum. In many cases, these differences can likely be attributed in part to country and award-specific factors. To establish whether there are systematic differences between the open formats beyond these specific factors, we run two regressions for each open format:

- **A regression against all formats.** The sample includes all band prices including those from sealed-bid auction.
- **A regression against open formats only.** The sample only includes band prices from the three open formats (SMRA, CCA and clock).

For the regressions of a format, we include the dummy and cross-products for that format type alongside the country and (significant) year fixed effects. We only include significant year fixed effects to increase the power of the test.

Table 2 provides the results for the CCA regressions. We include country fixed effects, any significant year fixed effects, a dummy to indicate whether the spectrum band was sub-1 GHz or mid-band spectrum and the cross-products of the CCA dummy and the three band types. The base case on the left-hand side (against all formats) is a sealed-bid, SMRA or clock auction for high-band spectrum. The base case on the right-hand side (against open formats) is either a SMRA or a clock auction for high-band spectrum. Both regressions show that low-band and high-band spectrum sell at a considerable premium in these base cases.

The cross-products with the CCA in both regressions are highlighted in red. The CCA achieves considerably higher low-band prices both when compared to all other formats as well as when compared to the open formats only.

Table 2: Impact of CCA on price compared to other formats

	Against all formats	Against open formats (clock and SMRA)
Low band	2.1 (0.18) ***	2.22 (0.18) ***
Mid band	1.19 (0.19) ***	1.33 (0.17) ***
Low band & CCA	1.16 (0.44) ***	1.03 (0.4) **
Mid band & CCA	-0.21 (0.62)	-0.47 (0.57)
High band & CCA	0.3 (0.53)	0.32 (0.54)
Significant year FE	Yes	Yes
Country FE	Yes	Yes
R-Squared	0.76	0.77
Observations	209	198

*Robust standard errors in parentheses. * 10% significance, ** 5% significance, *** 1% significance*

Table 3 provides the results for the SMRA regressions. The base case on the left-hand side (against all formats) is a sealed-bid, CCA or clock auction for high-band spectrum. The base case on the right-hand side (against open formats) is either a CCA or a clock auction for high-band spectrum. Both regressions show that low-band spectrum sell at a considerable premium in these base cases.

The cross-products with the SMRA in both regressions are highlighted in red. The SMRA achieves considerably lower prices for low-band spectrum when compared to the open formats only, but not when compared to all open formats. This may be a result of the considerably higher low-band prices achieved by the CCA (as evidenced by the results in Table 3).

Table 3: Impact of CCA on price compared to other formats

	Against all formats	Against open formats (clock and CCA)
Low band	2.49 (0.31) ***	2.69 (0.34) ***
Mid band	0.75 (0.4) *	0.66 (0.43)
Low band & SMRA	0.08 (0.43)	-0.89 (0.34) ***
Mid band & SMRA	1.07 (0.39) ***	0.4 (0.37)
High band & SMRA	0.54 (0.52)	-0.39 (0.44)
Significant year FE	Yes	Yes
Country FE	Yes	Yes
R-Squared	0.77	0.77
Observations	209	198

*Robust standard errors in parentheses. * 10% significance, ** 5% significance, *** 1% significance*

Table 4 provides the results for the clock auction regressions. The base case on the left-hand side (against all formats) is a sealed-bid, CCA or SMRA for high-band spectrum. The base case on the right-hand side (against open formats) is either a CCA or a SMRA for high-band spectrum. Both regressions show that low-band and mid-band spectrum sell at a considerable premium in these base cases.

The relevant interaction terms are highlighted in red. The clock auction does not lead to significantly different prices for any spectrum type, both when compared to all formats as well as when compared to the open formats only.

Table 4: Impact of CCA on price compared to other formats

	Against all formats	Against open formats (CCA and SMRA)
Low band	2.29 (0.2) ***	2.49 (0.19) ***
Mid band	1.13 (0.23) ***	1.21 (0.23) ***
Low band & Clock	-0.4 (0.38)	-0.08 (0.34)
Mid band & Clock	-0.24 (0.33)	-0.02 (0.27)
High band & Clock	0.02 (0.66)	0.36 (0.59)
Significant year FE	Yes	Yes
Country FE	Yes	Yes
R-Squared	0.75	0.75
Observations	209	198

*Robust standard errors in parentheses. * 10% significance, ** 5% significance, *** 1% significance*

6. Conclusion

Our results show that, for spectrum awards, open auction formats generally lead to higher revenues than sealed bid auction formats. This is consistent with auction theory that tells us that, in situations where bidders face significant common-value uncertainty, open formats promote price discovery leading to higher prices and more efficient outcomes.

The impact on price of a particular format depend on the type of spectrum being sold. We find that the CCA has led to significantly higher prices for sub-1 GHz spectrum, but that there is no significant difference for capacity spectrum. This may be due to the crucial nature of these bands at the time of award, so the stakes were undoubtedly higher for mobile operators to secure this spectrum and to ensure that rivals pay similar amounts.

A possible implication of this finding is that regulators should be cautious about using the CCA format for awards of critically important spectrum, such as low-band spectrum. Empirical evidence suggests that, under these circumstances, incentives for bidders to deviate from straightforward bidding may be pronounced, leading to distorted (higher) price outcomes and potential inefficiency in spectrum allocation.

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Authors

Hans-Martin Ihle is a Senior Consultant in NERA's Tokyo office, specialising in auctions and spectrum policy. Mr. Ihle has nearly 10 years of experience in the design and implementation of spectrum auctions. As a member of NERA's global Auctions Practice, he advises clients on auctions and regulatory issues in communications, energy, and other sectors worldwide, with a focus on the Asia Pacific region.

Richard Marsden is a Managing Director and leader of NERA's Radio Spectrum Practice, which focuses on the design of allocation mechanisms, including auctions and trading, bidding strategy, and related competition, pricing, regulatory, and public policy issues. Based in NERA's New York City and London offices, Mr. Marsden has 20 years of experience in microeconomics, political economy, and business consulting. He has worked for regulators and private companies in more than 40 countries across the Americas, Africa, Asia Pacific, and Europe. He has particular expertise in auction design and in applying economics to the telecommunications and media sectors.

Peter Traber is a Senior Analyst in NERA's Radio Spectrum Practice. Mr. Traber has supported regulators and governments worldwide in the design and implementation of spectrum auctions. He maintains and continuously expands NERA's Spectrum Database (covering more than 450 awards in over 70 countries since 1994).

Contact

For further information and questions please contact the authors:

Hans-Martin Ihle
Senior Consultant
Tokyo: +81 3 3500 3784
hans.ihle@nera.com

Richard Marsden
Managing Director
New York: +1 212 345 2981
richard.marsden@nera.com

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Notes

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- ¹¹ Koutroumpis and Cave, 2017, Auction Design and Auction Outcomes, https://papers.ssrn.com/sol3/papers.cfm?abstract_id=2958745
- ¹² Kwerel, Federal Communications Commission, 2000, "Spectrum Auctions Do Not Raise the Price of Wireless Services: Theory and Evidence", <http://wireless.fcc.gov/auctions/data/papersAndStudies/SpectrumAuctionsDoNotRaisePrices.pdf>
- ¹³ Wolfstetter, 2001, The Swiss UMTS Spectrum Auction Flop: Bad Luck or Bad Design?, https://www2.wiwi.hu-berlin.de/institute/wt1/research/2001/swiss_umts_flop.pdf
- ¹⁴ C. Cambini and N. Garelli, "Spectrum fees and market performance: A quantitative analysis", *Telecommunications Policy* (forthcoming, 2017).
- ¹⁵ Marsden, Ihle and Traber (2017), The Impact of High Spectrum Costs on Mobile Network Investment and Consumer Prices, 14th International Telecommunications Society (ITS) Asia-Pacific Regional Conference: "Mapping ICT into Transformation for the Next Information Society", Kyoto, Japan, 24-27 June, 2017, <https://www.econstor.eu/bitstream/10419/168518/1/Marsden-Ihle-Traber.pdf>
- ¹⁶ Excessively high spectrum licence fees are a way for governments to extort returns on sunk network investments. If firms perceive that their expected returns will be extracted in successive auctions, they will moderate their investment behaviour accordingly (and may even exit). William P. Rogerson, 1992, Contractual Solutions to the Hold-Up Problem, *Review of Economic Studies*, Vol 59, pp. 777-794.
- ¹⁷ New results in behavioural economics suggest that high and costly barriers to entry can be used as a signal by market participants to soften competition. In sectors with imperfect competition in which firms have some degree of flexibility over the prices they set, researchers have observed a tendency for prices to inflate over the theoretically efficient price if sunk costs are increased. Offerman and Potters, 2006, *Does Auctioning of Entry Licences Induce Collusion? An Experimental Study*. *Review of Economic Studies* (2006), Vol. 73, pp. 769-791. Buchheit and Feltovich, 2001, *Experimental Evidence of a Sunk-Cost Paradox: A study of Pricing Behavior in Bertrand—Edgeworth Duopoly*. *International Economic Review*, Vol. 52, pp. 317-347.
- ¹⁸ High upfront payments therefore reduce internal funds available for other projects. According to the pecking-order theory, developed by Myers and Majluf (1984), the cost of financing increases with asymmetric information. Internal funding is cheaper than external funding, as external providers of finance have much less information about these investments than the mobile operator and thus require a higher risk premium. Using external sources to fund these other projects may mean that they are no longer profitable, as returns may be insufficient to cover the higher risk premium. Stewart C. Myers and Nicholas S. Majluf, "Corporate financing and investment decisions when firms have information that investors do not have", *Journal of Financial Economics*, 13 (2): 187–221.
- ¹⁹ High auction prices may exhaust access to scarce lower cost internal funds and displace other investment activity. Access to capital from multinational parents or external sources may also be rationed in response to

low profitability in a market. In the literature, this phenomenon is referred to as “de-escalation” or “reverse sunk-cost effect” owing to financial constraints. See McAfee, Mialon, and Mialon, 2010, *Do Sunk Costs Matter?*, *Economic Inquiry*, Vol. 48, No.2 pp. 323-336.

²⁰ NERA maintains its own database of prices for mobile spectrum awards for countries around the world. This includes data on both upfront fees from auctions or direct awards, and, where relevant, incorporates annual fees for awarded spectrum. We used these prices to construct the dataset for this study.

²¹ In combinatorial auctions, bidders usually pay a price for an entire spectrum package which may not be easily decomposable into prices for spectrum in individual bands. In these cases, we have used the methodologies used by Ofcom in its consultation on annual licence fees for 900 and 1800 MHz licences. DotEcon, 2013, “800MHz and 2.6GHz linear reference prices and additional spectrum methodology”, <http://stakeholders.ofcom.org.uk/binaries/consultations/900-1800-mhz-fees/annexes/linear-reference-prices.pdf>.

²² The graphs also show that sealed bids are not commonly used for spectrum auctions. There are a considerably larger number of SMRAs, clocks and CCAs in our sample. The econometric results in the following section are robust though as the coefficients we estimate for them are all significant (“low-band” and “mid-band” dummies).