SPECTRUM AUCTIONS: THIRTY YEARS IN THE MAKING

Spectrum auctions are of strategic importance. Over the last three decades hundreds of spectrum auctions have taken place worldwide and billions of dollars have been spent.

The design of spectrum auctions has changed over this period, reflecting advances in understanding, technical innovations and experience. While some auctions have been complex and lengthy, where possible the trend is towards simpler auctions.

In this note we look at the evolution of spectrum auction design and implementation, and discuss the way bidders prepare their participation in auctions.

Art work, livestock, real estate, radio spectrum, wine, online advertising, and government securities are some of the many goods and services sold and procured by way of auction.

Billions of dollars of goods and services are transacted via auctions every year. Many auctions take place online through electronic auction platforms on the Internet.

Economics has played a significant role in shaping auctions, particularly radio spectrum auctions, and this was recognised by the Nobel Prize committee in Economics in 2020.

In this note we look at the evolution of spectrum auction design, policy and implementation, and discuss how bidders participate in these auctions.

Nobel Prize in Economics: Auction Design

Paul Milgrom and Robert Wilson were awarded the Nobel Prize in Economics in 2020 for "improvements to auction theory and inventions of new auction formats" when selling radio spectrum.

Stanford University Statement

Dawn of a new era

Before 1990 radio spectrum licences were awarded by comparative selection methods, known as beauty contests, by lottery, or on a first-come, first-served basis.

At the time these methods worked reasonably well, as demand for radio spectrum was accommodated by available supply, or regulatory oversight was such that comparative selection or beauty contests appealed.

Following the emergence of cellular telecoms in the 1980s and subsequent innovations that helped to stimulate the adoption of mobile phones, demand for some radio spectrum frequencies increased exponentially in the 1990s.

As a consequence, demand for mobile radio spectrum started to outstrip available supply.[1] Traditional licence award processes were stretched. In the US comparative selection methods were beset by litigation involving unsuccessful applicants arguing before the courts they were better entities to hold licences; and lottery allocations saw rent-seeking speculators acquiring licences with the intention of selling on to phone companies at a profit, often

[1] This supply-side constraint reflected past decisions where radio frequencies were allocated to uses that, at the time, were the highest value. When higher value mobile telephony uses emerged, these past decisions limited the amount of available radio frequency for mobile use.

resulting in delay.[2]

To overcome the drawbacks of administrative awards of spectrum licences, regulators started to look for market-based solutions.

In 1993 the US Congress empowered the FCC to use auctions when awarding new spectrum licences. Following advice from leading economists Paul Milgrom, Preston McAfee and Robert Wilson, the FCC applied an auction design that enabled the simultaneous sale of many thousands of spectrum licences (lots).

The first FCC spectrum auction in 1994 was modest in scale, with only 10 nationwide licences up for grabs. Nevertheless, it raised $617m and was regarded a huge success, paving the way for many subsequent auctions in the US and elsewhere.[3]

Since that first auction, over 100 spectrum auctions have been completed by the FCC, raising more than $230bn for the US Treasury. Among these was the biggest ever spectrum auction in terms of revenue which raised over $81bn in 2020.[4]

The FCC has also conducted four *reverse auctions* – where it was the single buyer of services from multiple sellers. These auctions have allocated over $10bn in public funds to support rollout of mobile phone and broadband services.

In 2016-17 an innovative *incentive auction* comprising a *forward auction* (the FCC as a single seller of spectrum rights and many buyers) and a reverse auction (the FCC as a single buyer of spectrum rights and many sellers) known as the broadcast incentive auction was undertaken. This auction incentivised TV broadcasters to *sell* radio spectrum rights in the 600 MHz band (the reverse auction) which were then repackaged and offered to mobile providers (the forward auction).[5]

Across the world

Following the successful application of spectrum auctions in the US in the 1990s, many other countries changed their spectrum licence award procedures away from administrative methods to auctions.

The then Radiocommunications Agency in the UK, under direction from government, undertook a spectrum auction for the first time in March 2000. Five nationwide spectrum licences in frequencies supporting the 3G mobile standard were auctioned using the *Simultaneous Multiple Round Ascending* (SMRA)[6] auction format, mirroring the format that had been applied successfully by the FCC in its early spectrum auctions in the 1990s.

The UK 3G auction raised around $34bn, at the time the largest ever amount grossed in a spectrum

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[2] Martin Spicer (1996) "International Survey of Spectrum Assignment for Cellular and PCS" Wireless Telecommunications Bureau, Federal Communications Commission (FCC), Washington DC, September at https://www.fcc.gov/sites/default/files/wireless/auctions/data/papersAndStudies/spicer.pdf

[3] Leading auction theorist and practitioner Peter Cramton commenting on this auction wrote: "This first auction was viewed by everyone as an experiment. The stakes were enormous. If the auction failed, it would mean that the FCC would have to rethink its entire auction strategy. Firms and consumers would have to tolerate further delays and more uncertainty. Fortunately, the auction was a huge success. Not only did the U.S. Treasury collect $617m, ten times more than preliminary estimates, but the licenses went to the bidders that valued them the most – the bidders most apt to make the best use of the spectrum. The time required to conduct the auction was just five days." See Cramton, P.C. (1995), "Money Out of Thin Air: The Nationwide Narrowband PCS Auction" *Journal of Economics & Management Strategy*, 4: 267-343. https://doi.org/10.1111/j.1430-9134.1995.00267.x

[4] https://www.fcc.gov/auction/107

[5] Bidding in the auction closed on March 30, 2017, repurposing 84 MHz of spectrum. The auction yielded $19.8bn in revenue, including $10.05bn for winning broadcast bidders and more than $7bn to be deposited to the U.S. Treasury for deficit reduction. https://www.fcc.gov/auction/1000

[6] The SMRA auction format presents multiple lots simultaneously in an ascending price setting. At the end of each round, for each lot receiving one or more bids the auction rules determine which bidder becomes the *standing high bidder* (sometimes *provisional winning bidder*) on each of these lots. A bidder bumped-off a standing high bid is free to bid on eligible lots in the next round, allowing the bidder an option to switch its bid to a different lot or lots. The SMRA auction ends when no new bids are made, after which the standing high bidders from the previous round are declared winners. The ascending bids should result in winners paying a price as bid and in theory these equal the valuations of the second-highest bidders.

auction. Four months later in August 2000, the German 3G auction sold six nationwide spectrum licences for $46bn, also using a SMRA format.

Auctions, efficiency and design

As Professor Peter Cramton noted after the first FCC auction, winners are likely those best able to use spectrum. This is what is meant by efficiency in regard of auction outcomes. To achieve efficiency, auctions need to be well-designed.

In seeking efficient outcomes, careful attention is paid by auction designers to the following considerations.

1. **Lot size and category**

   A key component when designing a spectrum auction is the description of lots for sale. Auctioneers organise lots (*frequency blocks*) into broad categories (*frequency bands*) which feature either *generic* (sometimes *abstract*) or *frequency specific* lots.[7]

   When frequency specific lots are offered, bidders have little discretion over the way frequencies are organised.[8] If a spectrum agency wishes to exert control over the quantity of frequencies used by operators in the delivery of services, it may choose to offer frequency specific lots.

   However, frequency specific lots are not used much these days, as spectrum agencies recognise generic lots enable better-informed market participants to organise frequencies. But this comes at the price of complexity, as two stages are required: (i) an initial allocation bidding stage aimed at bringing demand for lots into line with the supply of lots and (ii) an assignment stage in which winning bidders from the first stage bid to locate their winning lots into their preferred frequencies. See (7) below for more discussion on assignment procedures.

   With generic lots, fewer prices and hence fewer markets, are needed to achieve the goal of equating demand with supply. As some spectrum auctions feature small numbers of bidders, generic lots are better for promoting competition.

   In determining the size of a generic lot in a band, an auctioneer looks at criteria reflecting technology, market size and competition.

2. **Lot geography**

   In addition to the spectral characteristics of lots, an auctioneer considers the geographic reach of lots. In some instances, the propagation characteristics of spectrum favour local or small area licences (e.g. mmWave frequencies), whereas in other instances nationwide licences may be optimal.[9]

   If an auctioneer chooses local or small licences this allows bidders, rather than the auctioneer, to decide where geographic complementarities lie. Bidders would have more discretion in assembling packages of licenses that maximize the benefits from any geographic complementarities.[10]

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[7] For example, Ofcom in the UK offered 24 generic 5 MHz lots in its 2021 auction of frequencies in the 3.6-3.8 GHz band. https://www.ofcom.org.uk/__data/assets/pdf_file/0020/192413/statement-award-700mhz-3.6-3.8ghz-spectrum.pdf

[8] The Dutch 3G auction in the summer of 2000 featured 5 frequency specific lots A,B,C,D and E. See Eric van Damme (2002) "The Dutch UMTS-Auction" CESifo Working Paper, No. 722, Center for Economic Studies and ifo Institute (CESifo), Munich https://www.econstor.eu/bitstream/10419/75995/1/cesifo_wp722.pdf

[9] In large countries like Australia, Canada, India and the United States, spectrum auctions usually feature regional or local spectrum licences. In the United Kingdom, and many other European countries, spectrum auctions have often featured nationwide licences.

[10] Although localised licences offer greater bidder discretion, this can impose additional computational demands on bidders, especially in regard of bid strategy and valuation. In some circumstances this can result in inefficiency. In an econometric analysis of the US 'C Block' auctions of 1995-96, in which the FCC offered 480 distinct licence areas, Fox and Bajari (2013) argue that had the FCC chosen fewer licensed areas the outcome would have been more efficient. See Jeremy T. Fox and Patrick Bajari (2013) "Measuring the Efficiency of an FCC Spectrum Auction" *American Economic Journal: Microeconomics* vol. 5(1): pp.100–146, http://dx.doi.org/10.1257/mic.5.1.100

3. Reserve prices

Reserve prices are in part designed to deter non-serious participation and help progress a spectrum allocation process, as well as ensure government receives a certain minimum revenue reflecting opportunity cost.

It is important, however, that the auctioneer does not set the reserve price too high (i.e. above the market clearing price), as this could inhibit entry, frustrate price discovery and result in inefficiency (e.g. result in unsold spectrum). On the other hand, setting reserve prices too low may lengthen the time to complete the allocation process and delay service delivery to consumers.[11]

Further, governments should not seek to maximise auction revenue through the setting of reserve prices. As Hazlett and Muñoz (2009) argued, welfare is much higher when allocating spectrum focusses on the welfare associated with services delivered to consumers rather than on the revenue raised by selling spectrum inputs.[12]

In some spectrum auctions reserve prices have clearly been set too high. The Indian multiband 800 MHz, 900 MHz and 1800 MHz auction of 2013 witnessed excessively high reserve prices and as a result, only around 15% of the available spectrum was purchased.[13]

In some jurisdictions where reserve prices are directed by Government, policy is steered towards efficiency. This is the case in Australia where "In setting reserve prices, the Australian Communications and Media Authority (ACMA) and the Government should consider the influence of the reserve price on competitive behaviour, and the scope for price discovery through upward movement toward the market value of the spectrum"[14]

4. Bidder categorisation

An auctioneer may categorise bidders depending on their size, location and experience. In some spectrum auctions the auctioneer might be required to differentiate between incumbent holders of spectrum and new entrants. This could result in setting-aside frequency lots for entrants.

In the 2008 Advanced Wireless Services spectrum auction in Canada, the auctioneer set aside 40 MHz of the 2 GHz frequency band for new entrants.[15] Such a policy can distort spectrum prices if the auctioneer erroneously estimates the demand for

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[11] The length of time to complete an auction depends on various factors including the setting of reserve prices and allowable price increments. In the SMRA format, bidders increase bid prices subject to bid price rules (see bid collection (5)). If the auctioneer applies low price increments, this may cause an auction to last longer. An example of this occurred in the Polish 4G SMRA auction in 2015 which lasted 513 rounds. Both relatively low reserve prices and bid increments of 1% or 5% contributed to a significant lengthening of the bidding process, see Agnieszka Kuś (2020) "Polish experience from first-ever spectrum auction" *Telecommunications Policy*, vol. 44,7, https://doi.org/10.1016/j.telpol.2020.101971. The Portuguese multiband 5G SMRA auction in 2021 also suffered from design flaws: low price increments, low reserve prices (for 3.6 GHz) and too high reserve prices (for 700 MHz). The regulator ANACOM set price increments at 1%. The auction lasted 200 days over 1,727 rounds and 10 MHz of the 700 MHz went unsold with the rest sold at the reserve price. The auction design was criticized by Portugal's Prime Minister António Costa: "We all agree that the auction model that Anacom invented is, obviously, the worst possible auction model, it never ends and is causing an immense delay in the development of 5G in Portugal", see https://www.dinheirovivo.pt/empresas/telecomunicacoes/costa-o-modelo-do-leilao-do-5g-que-a-anacom-inventou-e-obviamente-o-pior-modelo-possivel-14239992.html The Portugal 5G auction results are at https://www.anacom.pt/render.jsp?contentId=1709636&languageId=1

[12] See Hazlett, T.W. and Muñoz, R.E. (2009), "A welfare analysis of spectrum allocation policies" *The RAND Journal of Economics*, 40: 424-454. https://doi.org/10.1111/j.1756-2171.2009.00072.x This paper implies that the cost of setting reserve prices too high is greater than the cost of setting them too low – so auctioneers should be conservative when setting reserve prices.

[13] See V.J. Christopher (2018) "A short analysis of spectrum auction in India", DOT, https://dot.gov.in/sites/default/files/auction_analysis.pdf

[14] See Department of Communications and the Arts (2018) "Spectrum Pricing – Review", Australian Government https://oia.pmc.gov.au/sites/default/files/posts/2021/06/spectrum_pricing_review.pdf

[15] See https://ised-isde.canada.ca/site/spectrum-management-telecommunications/en/spectrum-allocation/policy-framework-auction-spectrum-licences-advanced-wireless-services-and-other-spectrum-2-ghz-range#fig1

spectrum of new entrants. This was alleged by consultants advising one of the incumbent bidders in the Canadian 2 GHz auction.[16]

An alternative way to favour certain bidders such as new entrants or small rural players, is to extend bidding credits. The FCC applies bidding credits for certain types of bidders. Such bidders may be granted a percentage reduction on the auction bid price (e.g. 15%) up to a maximum cap.[17]

5. **Bid collection (how bid information is gathered from bidders)**

The way an auctioneer collects information from bidders depends on the type of auction held. In some instances, an auctioneer may collect information using a single-round bid format (e.g. sealed-bid auction). Alternatively, bid information may instead be gathered over multiple rounds.

A single round auction could be executed quickly and where the bidders are well-informed about the value of the lots, this may be optimal.

However, in a single-round auction bidders do not have an opportunity to discover information disclosed during the auction. As price discovery is often key to promoting efficiency and mitigating the *winner's curse* (see Text Box on p. 8), multi-round auction formats are often preferred.

However, multi-round auctions, depending on their design, can facilitate strategies that may lead to *strategic demand reduction* (or demand expansion). This gaming behaviour can be mitigated through other procedures constraining the nature of bidders' bidding activity and also through rules affecting information disclosure, see (9) and (10) below.

Notwithstanding strategic bidding considerations, most modern spectrum auctions feature multiple rounds so as to facilitate price discovery and stimulate competition.

How bids are expressed to the auctioneer may also be significant. Bids need to be expressive (reflect bidder valuations) and simple (easy to understand and process).

Any bid intuitively implies a willingness to pay for a package of lots (so-called atomistic bidding). In some auction formats, bidders may be able to express multiple bids for different packages. In this case, as discussed in the section 'Complex spectrum auctions' below, there may be exponentially many bid possibilities. An auctioneer may seek to apply constraints on the way bids are expressed in order to manage computational complexity in this case.[18]

The expression of bid increments in ascending auctions also plays a significant role, as discussed earlier in the context of reserve prices. In the SMRA format the auctioneer needs to determine permissible bid increments – which trade-off progression against strategic demand reduction.

In a well-designed SMRA, the auctioneer retains sufficient discretion over the setting of bid increments to manage progression. This was the case in Ofcom's 700 MHz and 3.6 GHz auction in 2021.[19]

Below we highlight how generic lots, and a clock auction format, is better for auction progression.

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[16] See NERA news report on advice given to operator TELUS https://www.nera.com/news-events/press-releases/2009/canadas-2008-radio-spectrum-auction-design-flawed-according-to.html

[17] See FCC (2015) https://docs.fcc.gov/public/attachments/DOC-334420A1.pdf

[18] On bidding languages and their application in complex auction settings, see Noam Nisan *et al* (eds) (2007) *Algorithmic Game Theory*, Cambridge University Press chapter 11 "Combinatorial Auctions".

[19] Ofcom advised bidders "The price increments we will use between rounds will be subject to Ofcom's discretion. However, our expectation is to use prices rounded in £1000s, and not to use increments greater than 20% or less than 2%. We also intend to limit the absolute price increase in each round in any lot category." See Ofcom (2021) Award of the 700 MHz and 3.6-3.8 GHz spectrum bands: Process guidance for potential applicants and bidders in the auction p. 18 https://www.ofcom.org.uk/__data/assets/pdf_file/0022/205546/700mhz-3.6-3.8ghz-spectrum-auction-process-guidance.pdf

6. **Winner determination (how winners are identified)**

   In auctions featuring frequency specific lots and no *package bidding*[20], it is relatively straightforward to identify winning bidders. A common winner determination procedure is the awarding of lots to bidders submitting the highest bids (or in a reverse auction, the lowest bids).

   In auctions featuring generic lots and in all auctions in which bidders may submit package bids, it may be less obvious which combination of bids are the winning bids. In this case, the auctioneer may apply algorithms to search for the combination of bids that win (the usual winner determination criterion is to look for the winning combination of bids that yields the highest auction revenue, where each bidder submits only one bid in that combination, and the allocation is feasible).[21]

7. **Assignment (which winner gets what)**

   The assignment procedure are rules that assign winners of generic lots to specific frequencies. For example, in an auction for radio spectrum licences, assignment involves a procedure for issuing licences with specific frequencies and allows spectrum managers to organise winning generic lots into *contiguous blocks*.[22] In most instances, an assignment stage invites sealed-bids in a single round format.

8. **Pricing rule (how bids determine the prices paid by winners)**

   The pricing rule procedure determines what winning bidders pay for lots. Rules may require bidders pay-as-bid (first-price), pay-as-clear (all successful bidders pay the same market clearing price) or pay an amount equal to the nearest unsuccessful bidder (second-price). In the assignment stage it is usual to apply second-price solutions. [23]

9. **Activity rules (constraints on bid activity)**

   Activity rules are crucially important and govern the number and type of lots a bidder can bid for in an auction. In general these may cover three dimensions: (i) the minimum quantity of lots a bidder is required to bid for; (ii) the maximum quantity of lots a bidder can bid for, and (iii) an overall bid activity constraint. Their purpose is to promote straightforward bidding (i.e. bids based on a bidder's valuation rather than influenced by other bidders' valuations), competition and progression.

   An auctioneer may require that a bidder must bid for a number of lots no lower than some minimum amount. This may apply, for example, where new entrants may be anticipated. The purpose of the rule is to ensure, absent package bidding opportunities, bidders do not end up winning an uneconomic quantity of spectrum.[24]

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[20] Package bids are where bidders express bid amounts for a package of lots. For example, if there are three lots A, B and C, {A,B} and {A,C} are two packages.

[21] The solution of the winner determination problem in a combinatorial auction is an integer linear programme (winners receive an integer value of lots). Optimisation problems like this are complex and difficult to solve. A good discussion on the issues is found in Maldoom, Dan (2007) "Winner determination and second pricing algorithms for combinatorial clock auctions", DotEcon Discussion Paper 07/01 https://www.dotecon.com/assets/images/dp0701.pdf

[22] Contiguous blocks are winning lots of frequency assembled into adjoining lots in terms of frequencies. For example, if a bidder wins five 200 MHz lots, the lots are contiguous when the lots extend over the frequencies X GHz to X+1 GHz.

[23] A well-known result in auction theory, due to Nobel Prize winning economist William Vickrey in 1961, asserts that a bidder can do no better in a second-price sealed-bid auction than by submitting a bid equal to their willingness to pay. In other words, bidders in this auction format may as well bid truthfully in accordance with their valuation. When all bidders do this, it leads to efficiency. If an auction format is ascending bid with multiple rounds, bidders may benefit by using bid strategies aimed at influencing other bidders' bids (gaming). The problem of gaming can be mitigated through bid activity rules. In an assignment stage, the pricing rule can be relatively complex and may involve prices that are nearest to Vickrey, see Ausubel and Baranov (2021) "The VCG Mechanism, the Core, and assignment stages in auctions", working paper http://www.obaranov.com/docs/Ausubel-Baranov-Assignment-Stage.pdf

[24] Although a bidder (such as a new entrant) can guard against winning an uneconomic quantity of spectrum by bidding for enough lots, in some auction formats like an SMRA auction, a bidder might be outbid on some of its lots and end up with too few lots to support its business case.

An auctioneer may place a cap on bids for lots, which may be bidder specific or across all bidders. Such spectrum caps are often attached when the auctioneer is concerned about competition in service markets that rely on spectrum inputs.

Bid activity rules help progress an auction and encourage bidders to bid in accordance with their valuations.[25] Typically, bid activity rules are applied by the auctioneer using a *points* measure of bid *activity.*

For example, each lot for each frequency category is assigned points by the auctioneer before the start of an auction. The points structure could reflect a pre-auction estimate of the relative value of lot categories.[26] A bidder's maximum activity in an auction is usually determined by its *initial eligibility*, which is the total number of activity points associated with the bidder's deposit.[27]

As part of the bid activity rules, the auctioneer chooses an *activity requirement* for each round. This usually works by determining the bidder's eligibility in each round. For example, the *activity requirement* might be such that a bidder can preserve its eligibility as long as its *processed activity* (the points it uses when bidding in a round) is 90% or more of its eligibility.[28] If a bidder's processed activity were less than 90%, its eligibility going into the next round is lowered.[29]

In an ascending auction the constraint applied on a bidder's activity in each round is set by the auctioneer to reflect the law of demand, as prices rise across lot categories, aggregate demand should fall. Consistent with this property of demand, bidders are usually not permitted to increase bid activity as prices increase. This ensures auction progression: as price increases, demand for lots in aggregate does not increase.[30]

Bid activity rules deter snake-in-the-grass bid sniping[31] – when bidders delay bidding in the hope of influencing other bidders' valuations and hence their demands.

10. Information disclosure (what information is made public when)

Information disclosure procedures determine what information is made public before,

[25] Activity rules may also allow for *waivers*, where bidders can sit out a round and remain active in the auction without submitting a bid. The motivation for waivers is to provide bidders additional time to consider ongoing participation. The downside of waivers is bidders may use them strategically. Another activity rule may permit bid *withdrawals*, to protect bidders against the risk of winning uneconomic lots. The downside of withdrawals is strategic bidding aimed at price driving.

[26] Consider an auction with ten lots in each of two lot categories 700 MHz and 1800 MHz. Suppose the reserve price per lot in 700 MHz is $10m and in 1800 MHz it is $30m. The auctioneer may assign ten points per 700 MHz lot and 30 points per 1800 MHz lot.

[27] A bidder submitting a deposit of $100m for the point structure given in the preceding footnote would receive 100 points. In round one the bidder would be able to bid on 3 lots in 1800 MHz and one lot in 700 MHz, or 4 lots in 700 MHz and 2 lots in 1800 MHz and so on.

[28] In this case 90% represents the activity requirement which is set by the auctioneer. The FCC often starts with an activity requirement of 85% or 90% and after a certain number of rounds it increases the activity requirement to 95% or higher. The ramping up of the activity requirement trades-off allowing bidders flexibility during the early rounds when price and package discovery are likely to be of greater value and promoting auction progression.

[29] Eligibility in round t+1 is usually equal to the smaller of (i) round t eligibility and (ii) processed activity in round t divided by the activity requirement in round t. For example, see section 8.1 in the Technical Guide to the FCC Auction 102 https://www.fcc.gov/file/14284/download

[30] In multi-round spectrum auctions with multiple lots, activity rules may reflect the revelation of individual bidders' preferences. This may, for example, apply via the application of something known as the generalized axiom of revealed preference (GARP), see Lawrence M. Ausubel and Oleg Baranov (2020) "Revealed Preference and Activity Rules in Dynamic Auctions", *International Economic Review*, vol 61, Issue 2, pp. 471-502.

[31] Bid-sniping occurs when bidders delay submitting bids until nearer the end of an auction in the hope of strategically lowering demand to win lots at a lower price. If all bidders behaved this way, progression would be delayed, bids would not reflect true valuations and efficiency threatened.

The Winner's Curse

This may occur in auctions for objects that have *common value*. Objects with common value are those where different individuals in possession of the **same** information about the object would arrive at the **same** estimate of value.

Consider a common value good offered in a single sealed-bid auction where the winner is the bidder submitting the highest bid. Each bidder knows that winning means likely paying a price above the true value of the object – giving rise to the winner's curse. This is because the best estimate of the object's hidden value is some weighted average of all the bidders' private estimates.

As a winning bid is based on one bidder's estimate it is above each of the estimates of the other bidders. Smart bidders know this ahead of the auction and shade their bids.

The effect of bidders shading bids would likely result in inefficiency. It may also lead to the auctioneer losing out on revenue.

The winner's curse can be mitigated by better auction design: e.g. having multiple rounds enables bidders to update estimates of value based on information *discovered* during bidding rounds.

during and after an auction. It also relates to information disclosed before a round, during a round and after a round. It relates to information about bids submitted, who is bidding, who bid what, etc.

Transparency and disclosure are viewed as favourable for price discovery and accountability. On the other hand, too much disclosure may foster anti-competitive bidder collusion and gaming.

Examples of information disclosure rules are making bidders' identities anonymous during the auction and revealing excess demand information in summary form. Such rules are intended to deter bidders from gaming.

Complex spectrum auctions

Although many spectrum auctions have followed the SMRA format pioneered by the FCC in the US, a number of auction innovations have occurred in practice outside the US. The most significant being those where bidders have been allowed to express package bids.[32] Package bidding opens up more bid possibilities and allows a bidder to express bids on combinations of lots. For example, bid $50m for three licences in cities {A,B,C} and $40m for two licences in cities {B,C}, etc.[33]

Package bidding overcomes a risk inherent with the SMRA format where a standing high bidder may be bumped-off one or more lots in subsequent rounds and end up winning an inferior package – this is known as *aggregation or exposure risk*.

For example, a bidder may be a standing high bidder on 4 x 200 MHz at £250m per lot in round 10. The bidder may value the 4 lots at £1.1bn. In round 11 new bids might result in the bidder eventually winning only two lots for £500m. But if the bidder values two lots at £200m per lot, it has been exposed to aggregation risk.

[32] The FCC has undertaken SMRA auctions in which bidders were allowed to present package bids for groups of licences pre-packaged by the FCC. For example, auction 73 in the 700 MHz band in 2008 featured packages of licences, see https://www.fcc.gov/auction/73

[33] Package bidding appeals to bidders when packaged lots have a different valuation than the sum of the individual valuations. Bid possibilities rise exponentially in the number of lots with package bidding. For example, with ten lots, there are 1,023 different bid possibilities. With 20 lots there are 1,048,575 different bid possibilities. More generally, with *n* lots the total combination of bid possibilities is 2^n-1. The standard approach in package auctions is to treat each bidder's bids as an *all-or-nothing* package bid, with the restriction that only one bid per bidder can win.

Where a bidder places value on aggregating lots (in our example 4 lots carry a per lot value above that of two lots), the SMRA format presents an exposure risk. This risk is eliminated if bidders can submit package bids.

In 2005, the Telecommunications Authority of Trinidad and Tobago applied the first practical application of package bidding within a complex spectrum auction known as the *Combinatorial Clock Auction* (CCA)[34] format.[35]

Although a CCA offers bidding flexibility and overcomes exposure risk, it comes at the cost of complexity; computationally for the auctioneer and in regard of devising bid strategies for bidders.[36]

Because of the complexity inherent in the second-price algorithms used to solve for winners and winning prices in a CCA, winning bidders know that winning prices may lie substantially below the amounts they bid.[37]

Although the CCA format has been used in a number of countries, it seems bidders and auctioneers prefer simpler auction formats. In practice, where there are many generic lots available, many auctioneers opt for the clock auction format these days to promote auction progression more effectively.

Clock auctions

The FCC and increasingly other spectrum agencies have shifted towards the use of *clock auctions* even for the cases where package bidding is absent or minimal.[38] This auction format works well when there are multiple generic lots.[39]

In a clock auction round-by-round price increments are set by the auctioneer, as in a typical SMRA. However, while a clock auction offers simultaneously multiple lots and prices ascend, it does *not* feature standing high bidders.

As a result, whenever demand exceeds supply at the end of a bidding round, the auction progresses and the posted-price for *all* the lots increases.[40] It is only

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[34] The CCA format is a two-stage bidding process. The first stage is a multiple round clock auction. In each round, the auctioneer announces prices for all lots and bidders respond with quantities demanded. If aggregate demand exceeds available supply for any lots, the auctioneer increases prices for these lots in the next round. The bidding process continues until prices reach a level at which aggregate demand is less than or equal to supply for every lot type. The second stage, known as the supplementary round, is a sealed-bid auction in which bidders can improve their bids made in the first stage and submit additional bids as desired for other combinations of lots.

[35] For more information see https://tatt.org.tt/AboutTATT/SpectrumManagement/FirstSpectrumAuction2005.aspx. Ofcom's 10–40 GHz and L-Band Auctions in 2008 were also among the first CCA auctions, see https://www.ofcom.org.uk/spectrum/spectrum-management/spectrum-awards. Other countries have also awarded spectrum licences using a CCA format, including Austria, Australia, Canada, Ireland and Switzerland.

[36] To manage complexity, regulators usually impose limits on the number of bids a bidder can submit in (the *supplementary round* of) a CCA, see Ausubel, L.M. and Baranov, O. (2017), "A Practical Guide to the Combinatorial Clock Auction" *Economic Journal* 127: F334-F350. https://doi.org/10.1111/ecoj.12404

[37] The CCA format can make it challenging for a bidder to communicate to investors regarding budget. Ofcom (2019) echoed this: "the main disadvantages of the CCA to be: bidders face a degree of uncertainty on the final outcome and prices of spectrum; budget constrained bidders may face challenges in their bidding decisions" see para. 2.16 in "Award of the 700 MHz and 3.6-3.8 GHz spectrum bands: Revised proposals on auction design" 28 October 2019 at https://www.ofcom.org.uk/__data/assets/pdf_file/0028/176648/revised-proposal-auction-design.pdf

[38] In Australia, the clock auction format discussed here is called an *Enhanced SMRA*. The terminology emphasizes that the format offers multiple lots simultaneously over multiple rounds in which the bid price ascends – with enhanced referring to a clock stage without standing high bidders. This format was applied in Australia for mmWave frequencies in 26 GHz in 2021. See https://www.acma.gov.au/about-spectrum-auctions and https://www.acma.gov.au/auction-summary-26-ghz-band-2021.

[39] Specifying a unit of frequency, for example 5 MHz, within a frequency band establishes a generic lot. For example, Ofcom offered 24 generic 5 MHz lots in its 2021 auction of frequencies in the 3.6-3.8 GHz band. See https://www.ofcom.org.uk/__data/assets/pdf_file/0020/192413/statement-award-700mhz-3.6-3.8ghz-spectrum.pdf

[40] In a SMRA the price increment applies to lots where standing high bidders are bumped off when other active bidders submit higher price bids. It may take many bidding rounds for all standing high bids to be bumped off and for the price to ascend. See also note 44 below and note 11 above.

when the ascending price bidding rounds finish that bidders discover how many lots they may have won. This is then followed by an assignment stage.

The main advantage of the clock auction format over a SMRA is *pace* because in every round all active bidders present bids (implicitly or explicitly).[41]

Achieving a faster pace in a clock auction runs the risk aggregate demand may fall short of supply – what may be termed overshooting – and potentially leave spectrum lots unsold and hence unused.

To mitigate overshooting in a clock auction, it is best practice to design rules that allow *carry-forward bids* and *intra-round* price bids.[42] Doing this ensures the auctioneer is not left with unsold lots and bidders have greater bidding flexibility.[43]

For example, if the lot price announced by the auctioneer increased from £80m to £90m, a bidder may submit, subject to activity rules, multiple bids that include demands expressed at prices between £80m and £90m.[44]

Ofcom, the UK regulator for communications services, claimed in a May 2022 consultation regarding a future auction that "the Clock format allows for a faster and *simpler auction design* because it removes the standing high bid mechanism, which is used in the SMRA".[45]

Bid teams, mock auctions and war rooms

A bidder participating in a spectrum auction usually establishes a bid team to advise on bid strategy (typically informed by game theory) and lot valuation. The significance of spectrum auctions is such that these often comprise senior management and appointed experts.[46]

Prior to an auction, a bid team will gather intelligence on the value of the lots and make assessments about

[41] If the German regulator BNetzA had applied a clock auction rather than an SMRA in its 5G auction in 2019, the auction may have concluded in many fewer rounds than the 497 rounds actually taken. For example, in the 3.6 GHz band 28 generic lots meant after a while it took 28 rounds to increase the price across all lots. See Dimpfl, Thomas and Reining, Alexander (2021) "Price discovery and learning during the German 5G auction", *Journal of Risk and Financial Management*, ISSN 1911-8074, MDPI, Basel, Vol. 14, Iss. 6, pp.1-17, https://doi.org/10.3390/jrfm14060274

[42] A carry-forward bid is where a bidder's bid in the previous round is carried-forward automatically into the current round. If the bidder were to submit a new bid, the carry-forward bid is effectively ignored. Carry-forward bids ensure that demand does not fall below supply in the current round. The inclusion of carry-forward bids and a requirement for bidders to meet a minimal activity at the beginning of a clock auction allows an auctioneer to increase the increment of the clock price without fear of demand crashing below supply. Intra-round price bids allow bidders to place one or more bids expressed at a price greater than or equal to the posted price from the previous round and less than or equal to the announced clock price for the current round. Intra-round bid prices allow bidders to fine tune changes in their demand, while allowing the auctioneer to affect the pace of the auction. These detailed rules have worked successfully in auctions conducted by the FCC and ISED (Innovation, Science and Economic Development) Canada.

[43] An alternative method is to hold a second phase of bidding for unsold lots. This method was applied by the Australian Communications and Media Authority (ACMA) in its 26 GHz spectrum auction in 2021 where it referred to its clock auction as an *enhanced SMRA*, see ACMA (2020) "26 GHz band auction, April 2021: Auction guide" December 2020 https://www.acma.gov.au/auction-summary-26-ghz-band-2021#background

[44] Bidding rules applying to intra-round price bids may require these bids to be *monotonic*: bid amounts should decrease or increase in ascending order of price bids.

[45] Para 9.27, page 110 Ofcom (2022) "Enabling mmWave spectrum for new uses: Making the 26 GHz and 40 GHz bands available for mobile technology" 9 May 2022 at https://www.ofcom.org.uk/__data/assets/pdf_file/0027/237258/mmwave-spectrum-condoc.pdf

[46] ACMA in Australia, like most spectrum auctioneers, advises that bidders "should obtain their own advice about their valuation of lots and bidding strategies" p.57, ACMA (2020) *op cit*. Forbes (2007) "Peeking into The Spectrum Auction" describes how experts advise bidders in FCC auctions: "Consultants and lawyers usually file the applications on behalf of companies. They also get tapped for a multitude of other tasks, including supervising auction deposits and payments and demystifying FCC regulations, such as the FCC's anti-collusion rule, which forbids discussions among bidders. Consultants and lawyers also may help craft business plans, determining, for instance, how particular licenses complement a firm's projects or other spectrum holdings, how much a particular slice of spectrum is worth and what an appropriate bidding strategy would be. They can even bid for clients--by phone or online--during the auction. Should a client win a license, they frequently step in and file additional forms and disclosures to the FCC." https://www.forbes.com/2007/12/27/spectrum-auction-wireless-tech-wire-cx_ew_1231auction.html?sh=3daaabc7520d

the valuations of other prospective bidders. This research, informed by company and market data, leads to a range of initial estimates of auction prices for the lots in an auction. All this helps manage stakeholder expectations and guide bid strategy.

To understand how the rules of an auction may impact outcomes, bid teams establish 'war rooms' – a dedicated facility (virtual or real) that facilitates confidential discussion regarding bid strategy and valuation analysis.[47]

Theoretically, in a well-designed auction rational bidders would unlikely benefit by using auction bid strategies other than submitting bids that are straightforward and in alignment with valuation. However, as Cramton and Ockenfels (2017) remark in their assessment of the 2010 German 4G auction "There is no perfect auction format."[48] In practice, spectrum auctions and specific detailed rules may leave open possibilities for strategic bidding.

Although bid strategy is often primarily focussed on acquiring spectrum at the lowest possible price, bidders sometimes seek to raise the price paid by rivals through *price driving* strategies. An example of this occurred in a SMRA multi-band auction in India in 2015 where one senior executive of a bidder remarked:[49]

"*It was really frustrating. We could see this guy was driving up the prices, without being serious about buying 900 MHz. But we couldn't do a thing. We just had to go higher and higher⋯we paid him back in the same coin in 800 MHz. That was some pleasure.*"[50]

In the 2.5 GHz FCC auction offering over 8,000 geographic licences, Verizon (bidding as Cellco Partnership) won only 12 licences scattered across the country for $1.5m.[51] According to some the spectrum is "useless" for Verizon and a New Street analyst asserted "They were clearly trying to drive the price up for T-Mobile".[52] In this instance, the price driving strategy was risky, left Verizon paying for spectrum they are unlikely to use and arguably failed because the $428m raised was far less than analyst expectations of around $3bn.[53]

Bidders and their bid teams when preparing for spectrum auctions can assess how different strategies, like price driving, may play out. Inside a 'war room' a bid team can engage in *mock-auctions* which also help familiarise management with the auction process.[54] These activities help shape the

[47] For example, in the UK 4G auction back in 2012 the bidders set up war rooms. See Financial Times (2012) "Bidders set up 4G war rooms to plot tactics" 20 December at https://www.ft.com/content/f22d6974-4aab-11e2-9650-00144feab49a.

[48] Peter Cramton and Axel Ockenfels (2017) "The German 4G Spectrum Auction: Design and Behaviour" *Economic Journal*, 127, pp. F305–F324. https://onlinelibrary.wiley.com/doi/pdfdirect/10.1111/ecoj.12406

[49] See https://economictimes.indiatimes.com/industry/telecom/spectrum-auction-how-telecom-companies-fought-the-rs-1-10-lakh-crore-battle/articleshow/46739345.cms

[50] Price driving of this kind does not impact efficiency in regard of an auction outcome, as the highest valuation bidders win but pay more due to other bidders' strategies. The outcome in India was unusual, as the SMRA format is prone to bidders engaging in strategic demand reduction, as rational bidders know that the price paid for the marginal unit affects the price of all lots won. However, in the case cited demands across 800 MHz and 900 MHz were asymmetric, opposite and known by the bidders. By contrast, in a CCA, small numbers of well-informed bidders may be associated with *strategic demand expansion*, as a bidder believing it will be the second-price knows it will determine the winning price of a rival. See Maarten C.W. Janssen and Vladimir Karamychev (2016) "Raising Rivals' Cost in Multi-unit Auctions" *International Journal of Industrial Organization* vol. 50.

[51] See https://www.sashajavid.com/FCC_Auction108.php

[52] See https://www.lightreading.com/5g/it-looks-like-verizon-accidentally-bought-$15m-worth-of-25ghz-spectrum/d/d-id/780140

[53] https://www.lightreading.com/5g/25ghz-spectrum-auction-ends-with-just-$428m-in-bids/d/d-id/780000

[54] Mock auctions are an important part of the formal auction process and help to ensure qualified bidders and the auctioneer fully understand the auction mechanics and procedures. For example, India's multi-band 5G auction in 2021 held a mock auction three days before the start of the auction proper. In a mock auction the auctioneer gives qualified bidders bidding scripts, with the object of testing the auction procedures and understanding of the auction mechanics rather than encourage strategic thinking. See p. 10 in "Notice Inviting Applications For Auction of Spectrum in 700 MHz, 800 MHz, 900 MHz, 1800 MHz, 2100 MHz, 2300 MHz & 2500 MHz Bands" Government of India, Ministry of Communications, Department of Telecommunications, 6 January 2021 at https://dot.gov.in/sites/default/files/Notice%20Inviting%20Applications%20%28NIA%29%202021_1.pdf

development of bid strategy and ensure auction software like *bid tracking tools* (BTT) or *auction tracking tools* are robustly tested.[55]

Bidders often find it valuable to build a BTT to reflect their preferences and help improve understanding about rivals' positions. A BTT also forms an important part of the communication process for a bidder's management. For example, it may include modules that automate key stakeholder notices after the end of each round of bidding (subject to auction rules about information disclosure).

A bidder's bid team also uses its expertise and knowledge to engage with the auctioneer during the run up to an auction. This will include making submissions to the auctioneer in respect of the detailed auction rules and procedures.

Although well-designed auctions contain a plethora of rules intended to obtain the right outcome in terms of economic efficiency, it is often the case that detailed scrutiny of specific auction rules can help a bidder towards advantageous strategies. At the very least, a knowledgeable bidder can avoid making mistakes and potentially save millions.

By the time an auction starts, all these activities should result in well-prepared bid teams.

[55] The FCC used to provide bidders with auction tracking tools, see https://www.fcc.gov/economics-analytics/auctions-division/auctions/auction-tracking-tools More recently the FCC utilizes a public reporting system accessible on the web: https://auctiondata.fcc.gov/

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