THE OUTLOOK FOR AUCTIONS

Einstein said, 'Make things as simple as possible, but not simpler.' As **MARTIN BICHLER** and **JACOB K. GOEREE** discuss, it's an axiom made for spectrum auctions

From 1994 to 2008, spectrum was sold almost exclusively using the simultaneous multiple round auction (SMRA). It is based on simple rules which make it easy to explain and implement, yet they create considerable strategic complexity. Since items have to be won one-by-one, bidders who compete aggressively for combinations of items risk paying too much if they ultimately win an inferior subset. This "exposure risk" suppresses bidding with adverse consequences for the auction's efficiency and revenue.

Since 2008, regulators worldwide have adopted the combinatorial clock auction (CCA) to avoid exposure problems. The CCA is based on very complex rules, but the premise was that bidding would be straightforward, i.e. bids would truthfully reflect valuations. Unfortunately, it is now well known that the CCA admits many other behaviours, including demand reduction, demand expansion, and predatory bidding. In particular, the CCA's supplementary stage may provide bidders with an opportunity to raise rivals' costs, which has led to some hard-to-defend outcomes.

In light of recent experiences with the CCA, regulators should be reassured about the advantages of combinatorial formats when synergies for adjacent geographic regions or contiguous blocks of spectrum are important. Market designers should beware of Einstein's advice and not regress to offering solutions that are too simplistic. Instead, they should take stock of two decades of field experience to pinpoint features essential to participating bidders and regulators. After all, spectrum auction design will only be truly successful if we are able to model their preferences correctly.

The standard paradigm in mechanism design assumes bidders with independent and private valuations, quasi-linear utility functions, and unlimited budgets, and regulators who aim to maximise efficiency or revenue of an auction in isolation, i.e. ignoring its effect on the downstream market. While these assumptions result in models that are elegant, they are not necessarily relevant. In what follows, we discuss objectives of regulators and bidders in spectrum auctions and how they differ from these "textbook" assumptions. These differences have an impact on the choice of the auction format. Furthermore, we discuss challenges for future auction designs and requirements for new models.

THE REGULATOR'S PERSPECTIVE

Even in the idealised textbook environment where bidders' values are independent and private, the preferred choice of auction is non-obvious as bidders' values for combinations may be sub-additive or super-additive. The former possibility implies that bidders treat the different items as substitutes, in which case the SMRA is predicted to perform perfectly.[1] The latter possibility turns out to be more realistic, however, which has stirred interest in combinatorial formats. These formats pose new design problems, as we discuss next.

Computational complexity and approximation. When bidders can express valuations for arbitrary combinations of items, optimal assignment becomes a computationally hard problem. Modern day optimisation software typically allows for (near) optimal solutions, although very large auctions can still pose a problem. For some auctions, such as the US incentive auction, the regulator may not be able to guarantee full optimality and may need to approximate the welfare-maximising allocation. This has led to fruitful research in computer science on approximation mechanisms that maintain truthfulness, but relax the goal of maximising welfare.[2] By now, worst-case bounds of approximation algorithms that satisfy strong game-theoretical equilibrium solution concepts are known for a number of problem types.[3] Sometimes, these worst-case bounds can be low, however. It is important to go beyond general worst-case analyses by taking prior knowledge about specific markets into account.

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Communication complexity and compact bid languages. Communication complexity is another fundamental problem. The term refers to the amount of information bidders need to communicate to be able to compute the efficient

allocation. For some spectrum auctions, such as in the Canadian auction in 2014, there were around 100 licences for sale. Bidders cannot possibly enumerate all packages ($\sim 21^{100}$ ignoring caps and floors) with the fully enumerative bid languages that have been used so far. Only a very small subset of all possible bids can be submitted and the vast majority will be missing. These "missing bids" are interpreted as expressing zero value by the winner-determination algorithm, causing inefficiencies and considerable randomness in allocations and prices.

Regulators need to be aware that higher expressiveness of the bid language does not necessarily lead to higher efficiency. Simplification has been introduced as a guiding principle in market design.[4,5] and the experimental results provide evidence that compact bid languages yield improved outcomes when there are many licences. This result has largely been ignored in spectrum auction design in the field.

Compact bid languages leverage prior information about the structure of the bidders' preferences and elicit these with a small number of parameters. Examples are hierarchical package bidding,[4] which reduces the packages allowed in the auction to a hierarchy, or domain-specific languages as they are used in procurement auctions.[6,7]

Policy goals and allocation constraints. Winner-determination algorithms pick the combination of bids that maximise seller revenue. The justification is that those with higher values can bid higher, so the revenue-maximising allocation also maximises the sum of bidders' values. In other words, by forcing bidders to "put their money where their mouths are", auctions result in efficient outcomes.

This argument, however, is persuasive only if the auction is being considered in isolation, i.e. without reference to the downstream market. Industry profits are highest when there is a monopoly, but it would be tenuous to praise the auction's efficiency when all spectrum is awarded to a single bidder. Indeed, regulators are more concerned with the well-functioning of the downstream market than revenue maximisation in the auction per se. They need to strike a balance between incentives for investments and efficiency and ensure enough competition in the end market to stimulate low consumer prices and quality of service.

To this end, regulators frequently use caps and set-aside licences to avoid undesired allocations or to encourage participation by entrants. It is important that regulators are able to implement such policy decisions in the mechanism. While it is simple to consider allocation constraints in an optimisation model computing the optimal allocation, such constraints have received little attention in the auction design literature, in particular with ascending auction designs.8

BIDDERS' PREFERENCES

Standard (spectrum) auction models assume that bidders' valuations are private and independent and that bidders have quasi-linear utility functions which aim to maximising payoff. While these assumptions are convenient for doing theory, models based on these idealised assumptions may lead to wrong advice for both bidders and regulators.

Value uncertainty, value interdependencies, and value endogeneity. Bidders spend substantial resources estimating the net present value of different spectrum packages prior to an auction. Such estimates, however, are highly uncertain. As a consequence, revenues in spectrum auctions are hard to predict. Even forecasts made just prior to an auction by investment banks tend to have high variance. For example, prior to the AWS auction in the US, analyst estimates of auction revenue ranged from $7 billion to $15 billion. Calculating the value of spectrum requires consideration of total market population, market penetration rates, market share, average revenue per unit, customer acquisition and activation costs, customer deactivations, etc. There are many other factors that make it hard to determine the value of spectrum.[9]

For example, the advent of media streaming and smartphones has probably led to a substantial change in valuations, compared to those that companies had 20 years ago. Such technical developments were probably not adequately considered in the valuations of the early spectrum auctions.

Note that value uncertainty can be specific to a bidder,[10] e.g. costs of roll out, or it can be common to all bidders, e.g. the adoption of new technologies such as media streaming. When both private and common value elements play role, auctions can no longer be fully efficient.[11,12,13] The intuition is that a bidder with more optimistic expectations about the rate of technology adoption may outbid a more pessimistic rival with lower costs. Second-best mechanisms, i.e. those achieving the highest possible (albeit less-than-full) efficiency, have not sufficiently been explored despite their obvious importance for (spectrum) auction design.

Finally, it should be noted that the design of the assignment mechanism, auction or otherwise, will affect bidders' valuations. If bidders know the next award will done via an efficient auction, they may have more incentives to invest (to generate higher values) than if spectrum will be awarded by lottery. So the valuations are endogenous to the choice of assignment mechanism. Of course, if auctions entail large transfers from the private to the public sector, investment incentives may be suppressed. Regulators concerned with quality of service might well prefer less competitive mechanisms that leave more rents for the bidders. In any case, value endogeneity is yet another reason why regulators' objectives are more complex than simply "welfare maximisation" or "revenue maximisation" within the auction.

Allocative externalities and anonymous pricing. Any spectrum auction is a unique event with important consequences for the competitive landscape that ensues afterward. The auction determines telecoms' positions in the aftermarket, and anticipating certain (dis)advantages associated with different outcomes, telecoms will adapt their bidding behavior in the auction accordingly.[14] For starters, telecoms will be interested in the entire allocation, not only in the packages they win and the prices they pay themselves. For example, the number of competitors and also their allocations can have a substantial impact on the revenues in the downstream market. End consumers pay a premium for the provider with the best network, and this is relative to rivals' spectrum holdings. In other words, the net present value of winning a set of spectrum licences also depends on the allocation to competitors.

In the German spectrum auction in 2000, for instance, six bidders could have closed the auction if they all reduced demand to two units at a total auction price of €30 billion, but two bidders eventually drove up the revenue to €50 billion (and then gave up). This was described as an attempt to drive out another bidder from the downstream market, and it shows that externalities can be substantial. Bichler et al.[15] discuss the impact of allocative externalities in the 2015 German spectrum auction and the role that the high transparency in the auction design played.

> **"Any auction is a unique event with important consequences for the competitive landscape."**

Being the "bandwidth leader" with the best connectivity can be a significant advantage in the end consumer market, and allocative externalities often play a role. However, the phenomenon has received relatively little attention in the literature.[16] The Vickrey-Clarke-Groves (VCG) mechanism would still determine the efficient allocation in dominant strategies, if bidders could express their preferences for all possible allocations. This, however, is unreasonable to assume in realistic markets due to the combinatorial explosion of possible allocations. Therefore, it is interesting to understand how bidders would bid in standard auction formats in the presence of allocative externalities, and how auction designs can address such externalities to avoid inefficiencies.

Telecoms operators care not only about what spectrum their rivals win but also how much they pay. The VCG mechanism and the two-stage CCA use non-anonymous payments, which can lead to undesirable outcomes. For example, in the 2012 Swiss spectrum auction that used the CCA, a small bidder (Sunrise) paid substantially more than a larger bidder (Swisscom) even though they won virtually the same amount of spectrum.

In high-stakes spectrum auctions, payments are in the billions of dollars and a much higher payment in the auction can be a significant disadvantage in the downstream market. Predatory strategies to raise rivals' costs have been observed in a number of applications of the two-stage CCA and have also been analysed theoretically.[17,18,19]

Principal-agent relationships and budget constraints. If financial markets were perfect, bidders would not face any budget constraints when acquiring valuable licences. In reality, budget constraints are almost always an issue, which challenges the quasi-linear utility assumption usually made in mechanism design. Furthermore, private budget constraints defy strategy-proof mechanisms, even if bidders' values are private and independent and they aim to maximise payoff.[20]

Budget constraints are often a result of principal-agent relationships in bidding teams, with the management taking the role of the agent and the board of directors that of the principal. While the agent may have a good estimate of the value of a particular package, the principal does not. The principal wants to maximise profit, i.e. value minus cost, but the agent might prefer more valuable packages to less valuable ones, irrespective of cost. In other words, agents try to win their most preferred package as long as it fits within the budget, while the principal pays the bill (usually billions of dollars). Bichler and Paulsen[21] explore environments where agents bid more aggressive than a principal would (if she possessed the agent's information), resulting in inefficient outcomes. Even though the principal controls the agent's budget, this may not be sufficient to incentivise the agent to bid optimally from the principal's viewpoint. In practice, the agent's hidden information makes the design of optimal contracts between principal and agent very difficult.

DISCUSSION

Spectrum auction design has seen considerable progress, but the journey has just begun. Two decades of implementation in the field has made clear that regulators' objectives and bidders' preferences differ from standard "textbook" assumptions. These differences require us to rethink all aspects of the auction's design, i.e. the process, the bid language, and the payment rule.

Auction process: sealed-bid vs iterative. Iterative auctions provide valuable price feedback to bidders over a series of rounds. This price feedback can reduce "winner's curse" concerns when value uncertainty plays a role.[22] It can also mitigate coordination problems, informing bidders about the intensity of their rivals' interests so that an informed trade-off between value and cost can be made.

Iterative auctions also make it easier for a board of directors to steer the bidding team during the course of an auction. In particular, iterative auctions may alleviate hidden-information problems and make it easier for the principal to implement their optimal strategy.[21]

In contrast, in sealed-bid auctions, value uncertainty can lead to surprising, and possibly problematic, outcomes. For example, in a first-price sealed-bid combinatorial auction conducted in Norway in 2013, one of the incumbents bid too low and did not win any spectrum. This incumbent was later forced to leave the market, and many argued this would not have happened if an iterative auction had been used.

Of course, the flip side is that entrants have better chances in sealed-bid formats, a point that has been advocated by Klemperer.[23] In an iterative auction, deep-pocketed incumbents have the opportunity to veto outcomes where entrants win licences by topping their bids in a next round (recall, e.g., the German year 2000 3G spectrum auction). Such pre-emptive behaviour is more difficult in sealed-bid formats, which have been adopted by some countries for this reason.

CHAPTER AND VERSE ON AUCTIONS

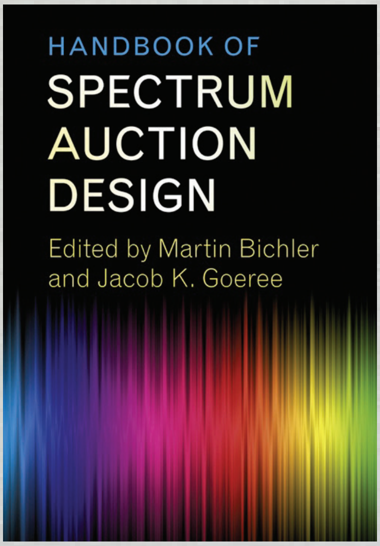
The *Handbook of Spectrum Auction Design* by Martin Bichler and Jacob K. Goeree is mammoth collection of papers that looks to have covered all there is to know about the theory and practice of designing auctions. Weighing in at 900 pages, contributors include pioneers and authorities such as Paul Milgrom, Peter Crampton and Paul Klemperer, who combine to give regulators and the industry details of the latest and sometimes highly complex developments in auctions that, as the editors says, are often played for "high stakes" around the world.

The book has 6 sections. The first two examine the key design methodologies of the simultaneous multiround auction (SMRA) and the combinatorial clock auction (CCA), with CCA being the one now in most use. This is reflected in the space allocated – just 4 chapters on SMRA and 13 on CCA.

One of the more accessible chapters is a practical guide to the CCA, which notes that although most academic work is now devoted to major theoretical issues surrounding this auction format, "many of the questions important for practical applications are overlooked" but apparently small details can be decisive for the auction's overall success. The writers warn regulators that custom design changes can contradict basic principles. While CCA is a flexible format, "naive integrations can introduce unintended consequences". This chapter also shows how the CCA approach can be flexible in helping to implement a key regulatory aim – downstream competition performance – but design flaws can creep in here.

The third part of the book examines alternative auction designs, some of which have been used in spectrum sales or evaluated by regulators. So while it may seem odd to see a chapter on the problem of allocating landing and take-off slots in a spectrum book, there is a good deal of commonality among all sorts of allocation issues. Approaches examined include "hierarchical package bidding" (notably used in a pivotal auction of 700 MHz spectrum in the US), and the "product-mix" auction.

Moving on, the editors include a selection of papers on experimental comparisons of auction designs. Just like in the pure sciences, it's possible to run "laboratory" experiments in economics, although it is still in its infancy, but as one chapter points out, its value



has been decisively demonstrated in auctions run by the FCC.

The last two parts of the book cover the bidders' perspective (a set of field reports from auction consultants showing the practicalities of implementation), and secondary markets and exchanges, about ensuring that spectrum can shift to new and more efficient uses as the market changes.

There's a wide "spectrum'" of accessible descriptive material and rather complex maths in this major book, and the editors are clearly well on top of this high-stakes subject. ***Marc Beishon***

And the flip side to the ability to solve coordination problems is that this resolution can, in principle, occur at any price levels. An iterative auction is more vulnerable to tacit collusion, e.g. when bidders decide on a strategy of mutual forbearance to divide the market as happened in the 1999 German spectrum auction.[24]

Bid language: expressiveness vs compactness. Combinatorial auctions provide bidders with a more flexible language to express their preferences for combinations of licences, which is important when value complementarities (synergies) exist. However, a fully enumerative bid language, which allows bidders to submit bids on every possible package suffers from the missing bids problem, i.e. bidders can only specify bids for a small subset of the exponentially many packages. The missing bids problem can lead to substantial inefficiencies.

A compact bid language is less demanding in that it lets bidders specify packages of licences with high synergies, but does not require an exponentially large set of bids. Hierarchical package bidding[4] is one example for a compact bidding language with regional licences. Compact bid languages can also be developed for the award of national licences with some prior knowledge about the main synergies for bidders.

Regulators also need to be able to express their preferences and constraints. For example, allocation constraints can be used in the winner determination to avoid very unequal distributions of spectrum, when the policy goal is to achieve a competitive end-consumer market. Such constraints are important and they need careful design.

Payment rules: non-anonymous vs anonymous. The VCG mechanism plays a central role in mechanism design theory. Externality pricing to support efficient assignment is persuasive in the narrow context of a single auction where bidders' values are exogenously given, but less so when bidders compete in a downstream market afterwards. If one bidder has to pay considerably more than another for the same spectrum, as can be the case with VCG or the two-stage CCA, then this will have consequences for the downstream market. From a regulator's perspective, externality-based pricing may be undesirable as it typically means that smaller bidders (entrants) end up paying more than larger bidders (incumbents), because the externality they impose is larger. Such an outcome has adverse consequences for the well-functioning of the downstream market. Anonymous and linear prices, such as used in the SMRA, HPB, or single-stage CCA, are preferable even if they do not necessarily lead to fully efficient outcomes.[25]

CONCLUSION

Every theoretical model is built on assumptions and it is important to have them in mind when providing policy advice. Assuming that bidders have private and independent values and that regulators simply maximise efficiency (or revenue) of the auction in isolation, leads to elegant but not necessarily relevant modeling. Bidders in spectrum auctions face substantial value uncertainty, allocative and informational externalities, long-tern investment concerns, budget constraints, etc. Regulators are mainly concerned about the well-functioning of the downstream market, which requires a careful choice not only of the auction rules, but also of anti-collusion rules, spectrum caps, set asides, etc.

Taking account of these details and constraints is crucially important when implementing spectrum auction designs in the field. As argued above, they necessitate careful reconsideration of the auction process (iterative vs sealed-bid), the bid language (compact vs fully enumerative), and the payment rule (anonymous vs. non-anonymous). As is typical in engineering disciplines, market designers often have to deal with changing, and sometimes conflicting, objectives. As such, it is unlikely that a single format will emerge that is preferable for all spectrum sales. For instance, large markets with many bidders and regional licences (such as in the US and Canada) require a different bid language than small national markets with only a few bidders.

While there is unlikely to be a one-size-fits-all design, two decades of spectrum sales in the field have affirmed Einstein's intuition that it is best to "make things as simple as possible, but not simpler". Simple pricing rules and simple bid languages can lead to high efficiency compared to complex ones (such as the CCA's "core pricing" and "fully expressive XOR bids"). That said, a bid language that is too simple, e.g. one that allows only for bids on individual licences (as in the SMRA), can lead to low efficiency in the presence of significant synergies.

Fortunately, spectrum auction designs that strike a balance between simplicity and flexibility exist and have been successfully employed in high-stakes applications since 2008. Intuitive and transparent package auction designs, resulting from careful theoretical, laboratory, and simulation analyses, hold great promise for spectrum and other applications.

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