A review of the evolution of auctions as a method for radio spectrum assignment

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1. Introduction

Radio spectrum is the means by which modern wireless communications are possible. It basically refers to the use of electromagnetic waves to code and transmit information. Spectrum can be regarded as a public good, which can be divided in portions or bands and used on the basis of time and geography. Governments everywhere took over management of spectrum and are responsible for allocating it to services, old and new, and assigned it to the many interested parties. Progress in the efficient use of the spectrum has allowed operators of wireless communications “squeeze in” more information using the same amount of spectrum or bandwidth that had been previously allocated. However, the explosive demand for wireless devices such as cell phones and smart terminals, and the upcoming explosion in all sorts of sensors and tracking devices making up the Internet of Things, greatly challenge the suppliers’ capacity to respond quickly to the increasing traffic and the government’s ability to allocate spectrum to its most efficient use.

The history of spectrum usage is relatively short but the changes occurred during an even shorter period of time have been remarkable, illustrating how technology keeps testing the ability of policy makers to balance out the interests involved in the utilization of spectrum: national defence, emergency services, broadcast TV and radio, telecommunications, navigation and aviation, satellite services.

The traditional approach to spectrum allocation is that spectrum is allocated to a certain use, which if commercially delivered becomes the main input to provide a telecommunications service. When several users need such resource to satisfy their communications needs or start a commercial service, spectrum needs to be assigned to one or more of those parties. Therefore, allocation and assignment have been intimately related and this relation became the standard process for spectrum utilization. International agreements and decisions by spectrum authorities would usually designate a band for a certain use with increasingly freedom as to the technology to be deployed. This is followed by an assignment process by which those deemed “most fit” to use the spectrum, would end up with exclusive rights to use it for a predetermined time. To solve the assignment problem, auctions have long been used.

This survey will help us understand the need for spectrum allocation management and the evolution of the auction as the main method of commercial spectrum assignment. It will consider spectrum as a public good whose utilization relies on two dimensions: frequency and geography, which have traditionally characterised the methods for allocation of spectrum. A license for using a set of frequencies (or band) is granted on a determined geographic area. The terms of the license include issues of interference and transmission power.

In the early days, individuals experimenting with new radio technologies were not concerned with organising the exploitation and commercial use of spectrum. As soon as its economic value was apparent disputes arose about the extent, to which anyone operating radio-transmitters was allowed to interfere with somebody else’s use of the same or adjacent bands. In the United States, the Federal Communications Commission received a congressional mandate to rule over the organization of the radio spectrum. Authorities and regulators across the world face many common problems and pressure from industry actors such as operators, electronic equipment manufacturers and advocacy groups. This survey will deal with historical aspects about the origins of spectrum organization, swiftly turning its focus on the utilization of auctions.

Given the huge success of spectrum auctions in raising revenue for governments, the survey will spend a great deal on the economic principles underlying auctions, reasons for them to become so widely used, the evolution of the particular mechanisms used for radio spectrum allocations and the current trends in spectrum auctions. The spectrum of interest for this survey is the one allowing the delivery of wireless and mobile telecommunications services, which started with the first generation of cellular telephony, spreading into broadband wireless access, and promising to revolutionize many sector of our economies through the deployment of 5G services and applications.

The goals of this paper are to establish the economic principles motivating the use of auctions, to introduce main auction formats used worldwide and the deficiencies detected throughout its application in the last fifteen years. The survey is structured as follows: section 2 discusses the early days in the need for spectrum allocation and assignment; it is mainly a tale of the way spectrum organisation and administration came under regulatory control in the United States. Section 3 briefly mentions the methods used before the 1990s for spectrum allocation of cellular telephony bands. Section 4 does a detailed description of the use of auctions as the predominant method, nowadays, for spectrum assignment, and section 5 describes the currently most widely used spectrum format. Section 6 discusses in detail the auction format adopted by the FCC to allocate spectrum for 5G, in one of the world's first allocation of spectrum in the millimetre wave bands. Section 7 concludes.

2. Early days in the use of spectrum

The turn of the 20th century witnessed the beginning of commercial use of radio spectrum mainly by ships crossing the North Atlantic. Regulation was proposed as a means to provide safety to the risky operations of commercial vessels. In 1910, the U.S. Department of the Navy rang the alarm in a letter to the Senate Committee on Commerce about the chaotic situation created by a disarranged crowd of independent radio operators whose transmissions drowned the help signals from vessels out in the sea.

In 1912, both the US Senate and the US House of Representatives passed a law that anyone operating a radio station was required to have a license. The license issuing power lay with the Secretary of Commerce. A license contained information about location of the station, the wavelengths approved for operation and the time the station was licensed to work, among others. The Act, as it came to be known, set out specific regulations for the Secretary of Commerce to act upon.

During the 1920s the radio broadcasting industry flourished. In the mid-1920s the lack of regulatory power that the Act had denied the Secretary of Commerce and the vigorous nascent industry - in a very short time hundreds of radio stations were started - combined to create 'chaos in broadcasting' (Coase, 1959). New stations would use any power of wavelength they wished, whereas the established stations found no reason to observe the conditions under which they had obtained their licenses.

Then, in 1927, the Congress in full passed measures to regulate the radio industry and brought into existence the Federal Radio Commission. The Commission was authorized to issue licences, which would state the technical terms of the granted use of wavelengths in an approved region. Licenses could not be transferred without Commission's approval and the Commission was prohibited from censoring programs. The 1927 Act gave the Commission a broader power to regulate the broadcasting industry.

In 1934, the Federal Communications Commission was created and the Radio Commission was absorbed. The FCC decided to base its allocation and assignment of radio frequencies on the "public interest" criterion, one of the three criteria in the 1927 Act – alongside "convenience" and "necessity"- that a broadcaster would have to further if it wanted to get a licensed (Hazlett, 1990). In Hazlett's words, the FCC decision exposed the "failure of the U.S. government to set a monetary price for the rental use of the airwaves".

Coase (1959) re-examined the need for federal regulation of the airwaves. The spread believe at the time was that radio frequencies were limited and demand for them was larger than the available number. Coase wondered that if almost all resources in economics facing scarcity used a pricing mechanism to sort out their allocation, the spectrum frequencies could also be subjected to a pricing mechanism. He then pointed at the role of property rights in the allocation of land without the need for government regulation. He remarked that the idea of using property rights and the pricing system in the allocation of frequencies were poorly understood and mostly unfamiliar to those in the broadcasting policy.

Coase emphatically defended the use of the pricing system in the allocation of radio frequencies for the broadcasting industry. He criticised the role of the FCC in carrying out the allocation process saying that a government agency would lack the "precise monetary measure of benefit and cost" that the market would provide instead, and such an agency would not be able to gather the relevant information, which the managers of companies using radio frequencies would certainly possess. He also vigorously disagreed with the Supreme Court who seemed to imply that using the pricing system would not be possible due to the limited supply of radio frequencies. Coase warned that most economic resources, in spite of being physically finite as well, relied on a pricing system for their allocation. In fact, he claimed that nothing in the technology of broadcasting would actually prevent the FCC using a pricing mechanism for the allocation of radio frequencies.

At the time, the right to use a frequency was defined by a short list of precisely defined attributes: right to use a wavelength during certain hours in a particular place. Coase advocated for a clear definition of those rights, property rights, adding that a pricing system would simply superimpose a payment. Government regulation of radio spectrum was introduced to prevent interference. However, Coase disagreed with the latter being the aim of regulation in the radio industry. Rather, he defended that the aim should be to maximize output.

3. Administrative process and lotteries

Before 1994, the method used by the FCC for spectrum allocation was an administrative decision. Companies, interested in and competing for one or more chunks of spectrum to operate broadcast or telecommunication services, had to file an application and the FCC would hold hearings whereby a decision was made on comparative grounds. Some commentators have deemed these hearings "beauty contests" and such denomination is common in the literature. Comparative hearings were replaced by lotteries, following a US Congress directive. Lotteries became faster means to allocate spectrum. The lottery participation requirements did not provide effective ways to exclude opportunists who were able to win spectrum licenses only to resell them later at an exorbitant profit.

Two issues must be looked at when comparing among different mechanisms: economic efficiency and fairness (CBO, 1992). A comparative hearing may not allocate a licence to the party with the highest value for it; in addition, a hearing may demand a substantial amount of resources from the interested parties and form the regulator as well. A lottery cannot assure an efficient allocation but rather a probability, usually small, may be calculated that the license ends up in the hands of those that value it the most. On the other hand, a lottery does not impose a burden on the spectrum administrator and may help save them resources. On the other hand, in a comparative hearing fairness may be compromised when legal and administrative costs are so high that only those who can afford them can participate. A lottery, on the contrary, has wider opportunities for a fair allocation but this happens at the risk of granting a windfall to the winner, like when winners are only opportunistic agents seeking to resell the rights.

4. Enter auctions

Both comparative hearings and lotteries were superseded in the United States by auctions with the first auctions being administered in 1994 for the allocation of personal communication services (PCS) spectrum bands (McMillan, 1994). In 1993, the US Congress mandated efficiency was to be sought when allocating spectrum and decided auctions would be used.

4.1. First uses of auctions to assign spectrum

The first country to pioneer the use of auctions in spectrum allocation was New Zealand which in 1990 used the second-price auction to allocate a suit of licenses – radio, television and cellular service- for broadcast TV (CBO, 1992). In 1991 the UK started auctioning the rights to TV programmes –defined by region, time of day, and day of the week - on a television channel; the auction was sealed-bid and typically the highest bidder was declared a winner (CBO, 1992). Later, in 1993 Australia used a first-price auction to sell two satellite TV service licenses (McMillan, 1994).

The 1994 US spectrum auctions were carried out after intense debate about the most efficient auction format to be used. The New Zealand and British experiences contributed key elements to the debate and decisions in the US. McMillan (1994) pointed at how the government was exposed to political criticism because, in spite of being theoretically efficient in that bidders reveal their true valuations, the second-price auction had the bidders paying the second highest bid. A second bid, in many cases is an extremely low value; as bidders reveal their willingness to pay, the public knows the extent of the gap between a bidder's willingness to pay and the price they actually pay. The later coupled with the lack of reserve prices created a hostile environment to the government when it was revealed that the auctions had only raised NZ $36 million instead of the $240 million the government's consultant had predicted (McMillan, 1994). In Britain auctions were used as a mechanism to replace the comparative hearings; in addition it was retained a criterion by which the regulator would judge whether a bidder meets a "public interest standard" (CBO, 1992).

4.2. FCC's adoption of spectrum auctions

The US experience demonstrated the importance of designing an auction, which is why this section focuses on the evolution of the original design proposed for the US market in 1993. Being a geographically quite extended country the FCC decided to divide up the country in regions while hoping to sell several licenses (blocks of frequencies) in each region. Therefore, the format of the new auctions would be such that all licenses – of a given type defined by the regulator - would be auction simultaneously. Understanding the enormous interests raised by the announcement that new blocks would be auctioned to allow operation of new mobile communications services (called PCS – Personal Communications Services – at the time), the FCC's auction design allowed for an efficient mode of "aggregating" several licenses when a bidder's business plan was to serve an extended area comprised of two or more regions. On the other hand, a bidder would find it to their advantage to be able to win a license in another area if reaching a point where the price of its original targeted region was out of its means.

The discussion above reflects one of the main problems that modern spectrum auctions face when several licenses, for instance disjoint geographical regions, are to be auctioned. The problem is the ability of an auction design to achieve efficiency when bidders regard several items as complements while other bidders may regards those items or a subset of them as complements.

Auction design is shaped by the objectives the regulator seeks to fulfil. Among them, first and foremost is the search of efficiency. The US Congress unambiguously mandated auctions would have to place spectrum licences in the hands of those who wold value it the most. Along with efficiency a regulator may pursue other objectives. In the 1994 US spectrum auctions the FCC sought to also promote other firms, such as minority-owned firms, to participate and win licences. The revenue objective came last in the list, but for many observers the auction became successful because of the amount of money it raised for the federal government.

In commenting on the complexities involved in the discussion and design processes at the time John McMillan writes: "Judgment and guesswork were needed to merge the various partial theories, to weigh the government's various objectives, to estimate the relative sizes of the different effects, and to evaluate whether a proposed scheme was workable" (McMillan, 1994: 151).

The FCC favoured an open auction format, giving up on a sealed-bid one. An open auction reduces the likelihood that upon auction's closure the winner finds himself regretting his purchase after finding out that he paid more than the licence is worth. The latter is known as the "winner's curse". Bidders who understand this typically bid cautiously. In a sealed-bid auction cautious bidders' bids might deviate too largely from the true value of the licence; when information about the price formation process of an auction is fed back to the bidders, as in an open auction, bidders will tend to be less cautious, increasing the probability of higher revenues.

Questions arise as to which auction for, open or sealed-bid, raises more revenue. In their seminal work Riley and Samuelson (1981) show that risk-averse bidders tend to bid higher in a sealed-bid auction than in an open auction. McMillan (1994) observes that determining which effect, the winner's curse or risk-aversion, dominates, and therefore makes bidders bid higher in one than in the other, is only be settled empirically. One other aspect that must be seriously addressed by auction designers is the effect of bidders' colluding behaviour. A sealed-bid auction is more effective against bidder collusion (Milgrom, 1987).

The auction design adopted in the US used a mixed form in which multiple licences are up for sale, with a starting price for each licence. Over a sequence of sealed-bid rounds the auctioneer asks bidders to raise their price, announcing a minimum increment in price over the last round's temporarily winning price. The auctioneer announces the provisional winner and his bid for each lot at the end of every round. The process continues until no bidder bids any higher.

This form was used to simultaneously auction a large number of spectrum licences which completely covered the continental territory of the United States. The auction is known as **Simultaneous Ascending Multiple Round** (SAMR) and was originally proposed by Paul Milgrom, Robert Wilson, and Preston McAfee (Cramton, 2012).

4.3. Evolution of the SAMR auction format

After its success in raising revenue for the US Treasury the SAMR became the most popular auction format embraced by many countries, especially a number of European nations that used it to assign spectrum for the operation of the newly developed 3G mobile technology.

Through the years, experience with the application of the SAMR auction has taught auction designers a few flaws or at least non-desirable situations that point out at needed improvements. In the final stages of the its first version design process, the SAMR auction was seen as vulnerable to "sniping" or the practice by a bidder of waiting until the auction's end to bid seriously (Cramton, 2012). An "activity rule' was then introduced for, which a bidder would have to be a "serious bidder' throughout the auction. The activity rule demands any bidder to keep valid bids for the licences he may be interested in winning, forcing the elimination of strategies that allow the bidder to hold back and wait.

Other very important problems arising from observation and analysis of the many times SAMR auction has been used are listed and explained in by Cramton (2012) and in his view the following are serious aspects to be worked through in any new auction design that attempts to improve or replace the basic SAMR auction format:

- *Demand reduction*: when bidders' demands exhibit some elasticity there may be incentives for bidders to reduce their demand and gain from such strategic behaviour. Weber (1997) illustrates the situation with one example: in the sale of two items, consider two bidders who value either item at *x* and the two items at *2*x*. If at any round a bidder is not the temporary winner of any item (from previous round) then the bidder bids the minimum asked price in the next round. If the bidder is the highest bidder on at least one item (from previous round) then the bidder does not submit any new bids. When the opening price is considerably below *x* and price increments are small compared to *x*, the auction ends in two rounds.

- *Tacit collusion*: the use of signalling strategies during the auction that allow bidders to communicate has been extensively studied since the first FCC auctions. Early on, the FCC realised that the last digits of a bid price, which normally were all zeros, were used I ways that bidders would signal other bidders their intended actions. The latter was possible because licences and bidders were assigned numerical codes; bidders intending to "say something to a competitor" found ways to convey messages by using the last digits of their bids. Even though the FCC decided the last digits in any bid would remain each equal to zero, when competition is weak bidders still may find the way to signal deals to their competitors that reduce the competition for licences, hence the prices.

- *Exposure*: In a SAMR auction bidders bid for individual licences, though if they prefer more than one, they will be bidding for them simultaneously. Therefore it is likely for a bidder to win some but not all of his preferred licences. Cramton (2012) rightly points it out: “this exposure to winning less than what the bidder needs has adverse consequences on efficiency”. The problem aggravates when there complementarities among the preferred licences.

- *Limited substitution across licences*: In the typical spectrum auction, the degree of substitutability among licences depends on the mix of geographical zones and frequency bands the regulator establishes. When several licences are offered and a different geographical subdivision scheme is used for each band the result is a decrease in the bidders' ability to substitute across blocks.

Most of the recent literature in auction design for spectrum assignment has revolved around finding alternatives or improved designs to overcome the problems presented above. In summarising the current concerns underlying the search for a more efficient auction format Cramton (2012) emphasizes three aspects of any new auction: i) substitution; ii) price discovery, and iii) truthful bidding.

Enhancing substitution is not only up to the auction format but also to the product design; the latter highlights the importance of understanding that different conceptions of the same product – for instance, two different partitions of the same geography - may lead to two different levels of auction outcome efficiency even if the same auction format is used.

Cramton claims that rarely a bidder has a complete valuation model for a spectrum licence; therefore a dynamic mechanism that provides the market with a collective insight is a vehicle to reduce price uncertainty. Price discovery is achieved through dynamic, open auctions that allow bidders learn about the price levels and the price growth sped.

Lastly, although inducing truthful bidding can be traced back to the seminal work of Vickrey (1961), its straightforward utilization was highly controversial the first time it was used to sell spectrum like the New Zealand experience in section 4.1 described. A generalization of the Vickrey pricing rule based in the Vickrey-Clarkes-Groove (VCG) mechanism is routinely used principally as a benchmark to assess the quality of the price of an auction.

4.4. The combinatorial auction

When a multi-unit auction such as most recent spectrum auctions around the world is administered using the SMAR format, the ability that bidders may wish to express their bid as a single bundle of items at a single price is foregone. Combinatorial auction is a proposed auction format that seeks to capture the need bidders have to express their preferences for **bundles** or **packages** instead of having to rely on either sequential auctions or simultaneous auctions where each individual bids have to be coordinated throughout the set of preferred licences.

Auctions, which do not allow to bid on bundles, present two main problems (CRA, 1997). When the objects in a set *K* are substitutes, the auction might create strategic incentives for a participant to “hide” his bid with the purpose of reducing the price; this situation is known as the demand reduction problem. For example, in the auctions for spectrum licences, the fact that a participant needs to get a group of licences might make the group price be higher than the sum of the prices that the participant would offer separately. Therefore, an auction, which does not encourage a bidder to bid on bundles, would give incentives to the bidder to reduce his bid for individual licences with a consequent price reduction (CRA, 1997). On the other hand, if the objects in *K* are complementary, a participant, who tries to “assemble” a packet of objects, is incurring the risk of only winning a part of it at a total price that exceeds his valuation; this problem is known as the exposure problem. Again, taking the spectrum licences as an example, a bidder who is not successful when bidding separately for a definite amount of licences may win a smaller set of them whose total price cannot be justified in absence of the complementary licences that he could not acquire.

In order to avoid the drawbacks of bidding individual prices for individual objects in a multiple-object auction, an auctioneer could rather use combinatorial auctions. In a combinatorial auction any bidder may place a bid for a subset of the set of auctioned objects. Package bidding allows participants in the auction the option of being able to bid on a group of lots instead of having to bid on each lot individually. This auction is theoretically appealing to bidders whose preferences for a set of licences exhibit complementarities. Package bidding eliminates the exposure problem. International experience with combinatorial auctions for spectrum is rather slim and as such there are limited examples of how to effectively implement package bidding in practice. The most important issue with combinatorial auctions is the difficult task of calculating the optimal solution of combination of packages when bids have been collected to decide who a winner is; this is known as bidder problem. There may also be a loss of transparency and difficulty of bidders to specify their bids in this type of auction.

Experimentally, (Ledyard et al., 1997) compares assignments resulting from sequential auctions, simultaneous auctions and combinatorial auctions in different environments. The results indicate that when the objects are substitute and homogeneous there is no difference between a sequential auction and an ascending auction. Second, the results obtained when considering heterogeneous groups with low synergy levels signal that the ascending auctions produce “better” allocations than sequential auctions. And, finally, when considering complementary heterogeneous objects, combinatorial auctions behave better than ascending auctions and sequential auctions in terms of efficiency and revenue. Cybernomics Inc. in the United States reported the results of experiments with combinatorial auctions for radio spectrum licences (Cybernomics Inc., 2000). In these experiments, the auctions were “fictitious” and the participants placed the bids following a pre-established design of preferences: each participant was told the “synergy” degree between the licences in each experiment. The results of these controlled environments suggested that the combinatorial auctions have a better performance concerning the efficiency in the assignment but not regarding the revenue for the auctioneer in all the instances analyzed.

One of the drawbacks of combinatorial auctions is the computational complexity of the winner determination problem. This problem can be formulated as an integer optimization model, which is “hard” to solve, that aims at maximizing the revenue of the auctioneer as long as the auctioneer allocates disjoint sets to the winners. The restrictions assert that each object be assigned once and that each participant obtains a subset of objects at the most.

Combinatorial auctions may be static (one round) or dynamic (multiple rounds). In the first case, the participants report their bids for each one of the subsets of objects and the winners are determined. In the second case, the bids from the participants compete during several rounds in a way that the assignments are determined by the winning bids in the last round. The main difference between the two types of mechanisms is in the information available for the participants at the time of bidding.

According to (Ausubel & Milgrom, 2002) and (Ausubel, 1997) an efficient auction design should have the following characteristics:

- The mechanism must maximize the information available to the participants at the moment of bidding.
- The structure of the auction must be such that the payments for the participants do not depend on the bids.
- The resulting assignment must be efficienti.

Therefore, a dynamic auction has advantages over a static auction because in the former the bidders have more information available at the moment of bidding than in the latter.

When the objects are identical and substitute for all of the participants, an efficient static format is the Vickrey auction and its extension to a dynamic format is the Ausubel auction (Ausubel, 1997). For non-identical objects that allow the existence of complementary relations, the static format stems from the VCG mechanism (Ausubel 1997), yielding efficient assignments. The corresponding auction is a combinatorial auction, which uses the payment rule of the Vickrey auction. Regarding extensions to a dynamic format, (Ausubel & Milgrom, 2002) presents an ascending auction in which the participants are allowed to bid for bundles. In each round, the bid for a bundle must be positive and greater than the best bid from the previous round. After each round, the auctioneer determines the set of potential winning bids so that the total revenue is maximized. The auction continues in a sequence of rounds until none of the participants bid anymore. When there are no new bids, the auction ends and the winning bids correspond to those of the round. The results of this auction are efficient assignments. This auction is an extension of the ascending auction used by the FCC, in the way that the participants can bid for bundles of objects (Ausubel a& Milgrom, 1997). In the results of the experiments presented in (Ledyard et al., 1997) the mechanism performed poorly - vis-à-vis the efficiency in the assignment and revenue of the auctioneer - when the objects of the auction were complements or appeared to be complements at some degree.

New formats are being proposed. A common concern is that those new proposal address the issues raised by the experts in order to increase the efficiency of the auction. Hybrid models where a dynamic stage is followed by a static, combinatorial stage is gaining increasing favourability by the concerned agencies mainly in the US and Europe.

5. Clock auctions and bundle bidding

The introduction of the **Combinatorial Clock Auction** (CCA) in 2006 marks a new stage in the utilisation of auctions for spectrum assignment. In a CCA a set of products is for sale; a product identifies a number of licenses in a given geographical region; those licenses are also known as units or blocks. The essential CCA design consists of two main stages: the Allocation stage and the Assignment stage; in turn, the allocation stage is further divided in two: the Clock Rounds and the Supplementary Round (Industry Canada, 2013).

In the auction, all bidders bid during the Clock Rounds and, possibly, fewer are allowed into the Supplementary round. The Supplementary round is a one-time combinatorial auction whereby all bids (bundles and respective prices) made by a bidder in the Clock Rounds are included in addition to the bundles the bidders wants to submit. After the winner determination problem is solved, only the winners of at least one item of products with two or more licenses get to bid on specific targeted licenses in the Assignment stage.

5.1. Eligibility and activity

Previous to auction start the auctioneer uses a point system to allocate “weights” to every unit of every product. Such weights provide an initial guide to the value of licenses and are used so that every bidder sets a number of points for herself to get started. Such number is called initial eligibility. As every round reveals individual, unitary prices for the auctioned products, bidders respond by demanding a number of units of each product; the sum of points of those demanded units is called the bidder’s “activity level”. In the next round prices increase, though price increments in two different products are not necessarily the same.

On a given clock round a bidder’s activity level value is the sum of points of those products included in the bidder’s bid. The bidder’s eligibility level is a measure of how “large” a bidder’s bid can be at any round. Before the auction starts bidders choose their initial eligibility levels; then eligibility is maintained if the bidder’s activity level remains equal to the eligibility, or is decreased when the activity level is reduced. The round at which this happens is known as an eligibility-reducing round. The latter results in next round eligibility being set equal to the new, reduced activity level. Thus, a bidder’s activity should be equal or less than her eligibility; this is called the activity rule.

Activity rules seek to induce bidders to bid on the items they really prefer forcing them to do so in a way that keeps them actively bidding throughout the auction. With such a rule in place the hideouts for bidders are minimised.

When a round closes, bidders are informed about the excess demand for each product. That is, the sum of all units demanded for each product less the number of units offered by the auctioneer.

5.2. Exception to the rule: allowing rational bids

There is an exception to the activity rule: a bidder is allowed to bid on a bundle whose eligibility is greater than the bidder’s current eligibility if the Revealed Preference Condition (RPC) is met. The RPC allows a bidder to explore bundles whose eligibility exceeds the bidder’s current eligibility. During the clock rounds a bidder may be focused on a particular bundle, with prices for the licenses in the bundle going up as his eligibility is possibly going down. Because of such focus, the bidder may have overlooked an opportunity to bid on an alternative group of licenses whose price is lower than the current price held by the bundle he is focused on, though with an eligibility higher than his current eligibility. If the auction used only activity-based rule such bundle would be out of reach by the bidder. So the RPC allow bidders to bid on an eligibility-rule breaking bundle for which they may have some preference even if they were not highly attractive at earlier times.

RPC imposes a condition on the relative prices of two bundles, namely, the new bundle q_t which breaks the eligibility condition and each of the bundles, say q_s for $s < t$, where an eligibility-reducing round occurred. Assuming that at round t a bidder has devised a bundle q_t as attractive, if the eligibility of q_t surpasses the bidder’s current eligibility, the bidder can still place a valid bid for q_t if the following condition (RPC) holds:

For every eligibility-reducing round *s* (*s* < *t*),

$$x_t - x_s \leq y_t - y_s$$

where $x_t = p_t \cdot q_t$, is the price of the new bundle q_t at round-*t* prices p_t
$x_s = p_s \cdot q_t$, is the price of the new bundle q_t at round-*s* prices p_s
$y_t = p_t \cdot q_s$, is the price of bundle q_s at round-*t* prices p_t
$y_s = p_s \cdot q_s$, is the price of bundle q_s at round-*s* prices p_s

The latter means that as long as the relative price of the new bundle is less than the relative price of each of the bundles demanded at eligibility-reducing rounds, the new bid is valid even if it violates the eligibility condition.

The auction essentially ends with the Supplementary Round where prices are determined using a Vickrey-related pricing rule. In fact, the Vickrey-Clark-Groves[1] (VCG) price is first calculated for each winning bundle upon which a condition is further imposed; such condition demands the price be in the core of a certain cooperative game, which is proved to be non-empty. If the price is not in the core then a core price is calculated such that it is the nearest price to the VCG previously calculated. The obtained core price is used to charge the bidder who bid on such bundle.

6. Auctioning spectrum for 5G in the US

As of late 2018 and early 2019 the US FCC administered two auctions, Auction 101 and Auction 102, to sell spectrum in millimetre wave bands, namely the 28 GHz and the 24 GHz bands. The auctions triggered the allocation of spectrum for 5G in the world.

As stated in (FCC, 2018) Auction 102 offered 2,912 licenses in the 24 GHz band with geographical extent of each license based on Partial Economic Areas (PEAs). Two licenses, in the 24.25–24.45 GHz band were offered as two 100-MHz blocks; these licenses were said to type L. In addition, five licenses in the 24.75–25.25 GHz band were offered as five 100-MHz blocks; these licenses were said to type U.

Auction 102 used a somewhat different format than previously tried I the US. In the auction a **product** is a pairing of a PEA and a license type. For each of the 832 PEAs a bidder would bid for up to 2 L licenses and up to 5 U licenses. Combining the 3 options in the Lower band set, that is, bidding for either 0, 1 or 2 blocks, with the 6 options in the Upper band set, that is, bidding for either 0, 1, 2, . . ., or 5 blocks, the total number of combinations was 3*6*832.

Auction 102 proceeded in rounds. Unlike the Canadian CCAs, Auction 102 allowed a bidder to express its preferences in a much richer language: the auction introduced **intra-round** bidding. On a given round k, two price bounds are defined: the lower bound known as the posted price, PP_{k-1}, (the formed price from the previous round k-1) and the clock price,

[1] The Vickrey-Clarke-Groves auction, VCG, is a true, socially optimal mechanism for the assignment of multiple objects. By encouraging offers to reveal the true assessment that a participant has for the auctioned object, the VCG auction is efficient. The price paid by a participating agent X in the VCG auction has been popularly described as "the marginal cost that such agent causes to the other participants." In essence, it is a question of calculating the difference (the “marginal”) between the value generated by the auction when X does not participate and (less) the value generated by the auction by the other participants (when X does participate). The second price auction of a single object serves to illustrate this definition: having won the second price auction, if X were excluded from it, the winner would have been the one who had offered the second highest value, P. With P being the real valuation of such bidder and with no other participant the auction deriving a positive value (since they have did not win), the first term of the VCG price is P. On the other hand, when X participates, the value accrued to all those other bidders is zero because none won. Thus, P - 0 = P, is the VCG price in the second price auction.

CP_k, (the announced price for the current round k). A bidder may then submit one of two types of bids (see next paragraph) with prices in the [PP_{k-1}, CP_k] interval.

The restrictions are: same amount cannot bid at two different prices, and same price cannot be bid for two different amounts. Excluding those restricted bids, once all bids are collected the bidding system orders all the bids by price and starts awarding blocks according to that ordering, the typical sorting of (quantity, price) bids in a multi-unit, identical unit auction. In general the processing of bids may result in some units being won (temporarily) by the bidder at a price and other units at a different price after the round closes.

There are two type of bids, which cannot be used together in a single round: a bid can be simple or switch. Compared to that of the CCA, these two in-round mutually exclusive options enrich the bidder's preference expression. A simple bid is a collection of pairs indicating an amount and a price. A better way to understand this is that a simple bid expresses the bidder's demand curve in the price interval [PP_{k-1}, CP_k]. A switch bid allows the bidder to exchange a number of blocks won (in a previous rounds) from one category to the opposite category (for instance, the bidder wants to switch 2 U-Category blocks that have been temporarily won to 2 L-Category blocks, within the same PEA)

In summary, for each PEA a bid can be placed either as a collection of (quantity, price) pairs, which can be understood as the bidder partially revealing his demand function, or as a condition that asks for swapping blocks that the bidder is temporarily winning from the previous round with blocks of the opposite category, within the same PEA. The former is known as simple bid whereas the latter is a switch bid.

The process by which the auctioneer decides at each round who gets which blocks of a given product (PEA plus license category) and the price, at which they (temporarily) get them, is known as the **demand process**. The process collects the bids (simple or switch) from bidders and, excluding the restricted bids, then it orders the bids by price and starts awarding blocks according to that ordering. This is similar to multi-unit auctions whereby the highest price bid is first allocated the number of demanded units, and then if supply has not been exhausted the next highest price will be allocated its associated demand or partial demand if the remaining supply is exhausted, and so on. In other words, blocks are assigned to highest bids until supply gets exhausted; these are the temporary winners and the auctioneer will inform them about it. Other bidders, who win nothing, will just get news about the aggregate demand on the round (the sum of all demanded blocks by all bidders).

The demand process puts the sorted bids in a queue, and as bids are processed, they are deemed either fully acceptable bids or partially acceptable bids. If a bid is fully acceptable then it is removed from the queue, while the bidder submitting such bid is granted the blocks demanded. If the demand process cannot fully satisfy a bid, the bid is deemed partially acceptable; part of it is allocated to the bidder and the bid is returned to the queue. The auction ends when either no new bids are received or the demand process determines no valid bids were processed.

7. Conclusions

A license for using a set of radio frequencies (or band) is granted on a determined geographic area. The terms of the license include issues of interference and transmission power. This survey helps us understand the need for granting rights to protect spectrum users from interference and path chosen by many governments towards spectrum rights allocation by means of an auction. It acknowledges the auction as an effective mechanism to allocate spectrum, while reviewing the main features of the most frequently used auction formats over the last 30 years.

While describing and explaining the mechanics of the auction formats included, it does so by highlighting the economic and policy issues that arise as conflictive or weak and need to be improved. Such approach reasserts the evolution of the mechanism from selling a single object to selling multiple objects with a range of conditions and rules that seek to increase the efficiency of the outcome. Such auction designs, in particular, have acknowledge the need for more flexibility and creativity in the expression of preferences, while doing its best to deter collusion, with rules that either incentivise behaviour that aligns with the bidder's objectives or deter bidders from unwanted behaviour.

Looking forward, with the advent of software-defined radio, more commonly known as cognitive radio technology, transmitting devices are able to learn whether particular spectrum bands are being used or not at a given time. The ability of such technology to use opportunistically the spectrum without creating damaging interference introduces a new dimension to the problem. In other words, spectrum sharing is now positioning itself as a strong alternative to exclusive rights, which may have an important impact on the current spectrum allocation practices, which include selling the spectrum via an auction.

References

Ausubel, Lawrence. (1997). An efficient ascending bid auction for multiple objects. Working paper, University of Maryland.

Ausubel, Lawrence, and Paul Milgrom. (2002). Ascending auctions with package bidding, Frontiers of Theoretical Economics, vol. 1, No. 1

Congressional Budget Office. (1992). Auctioning Radio Spectrum Licenses, Washington DC, March.

Coase, R. (1959). The Federal Communications Commission, *Journal of Law and Economics*, 2, 1-40.

CRA and MarketDesign. (1997). Report 1b: Package bidding for spectrum licenses, Federal Communications Commission, FCC.

Cramton, P. (2013). Spectrum Auction Design, *Review of Industrial Organization*, 42:2, forthcoming.

Cramton, P. (2006). Simultaneous Ascending Auctions, in Peter Cramton, Yoav Shoham, and Richard Steinberg (eds.), *Combinatorial Auctions*, Chapter 4, 99-114, MIT Press.

Cramton, P. (1997). The FCC Spectrum Auctions: An Early Assessment, *Journal of Economics and Management Strategy*, 6:3, 431-495.

Cybernomics, Inc. (2000). An experimental comparison of the simultaneous multi-round auction and the CRA combinatorial auction. Submitted to the Federal Communications Commission Contract Number C-9854019.

Federal Communications Commission (2018). Auctions for Upper microwave flexible use licenses for next-generation wireless services. FCC 18-109

Hazlett, T.W, Muñoz, R.E. & Avanzini, D.B. (2012). What Really Matters in Spectrum Allocation Design. *Northwestern Journal of Technology and Intellectual Property*. Vol. 10, No. 3. Winter.

Hazlett, T. (1990). The rationality of U.S. regulation of the broadcast spectrum, *Journal of Law and Economics*, 33, 133-.

Industry Canada (2013). Licensing Framework for Mobile Broadband Services (MBS) — 700 MHz Band.

Krishna, V. (2002). Auction Theory. Academic Press, 1st ed.

Ledyard, J.O., Porter, D. & Rangel, A. (1997). Experiments testing multiobject allocation mechanisms, *Journal of Economics & Management Strategy*, vol. 6, No. 3.

McMillan, J. (1994). Selling spectrum rights, *Journal of Economic Perspectives*, 8:3, 145-162.

Milgrom, P. (1987). Auction theory. In Bewley, T., ed., Advances in Economic Theory. Cambridge University Press, 1-32.

Riley, J. & Samuelson, W.(1981), Optimal Auctions, American Economic Review, 71, 381-92.

Vickrey, William. (1961). Counterspeculation, auctions and competitive sealed tenders, *The Journal of Finance*, vol. 16, no. 1.

Weber, R.J. (1997). Making more from less: strategic demand redudtion in the FCC spectrum auctions. *Journal of Economics and Management Strategy*, Vol. 6, No. 3, 529-548.