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Spectrum auction design: Simple auctions for complex sales

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ABSTRACT

Following the successful PCS Auction conducted by the US Federal Communications Commission in 1994, auctions have replaced traditional ways of allocating valuable radio spectrum. Spectrum auctions have raised hundreds of billion dollars worldwide and have become a role model for market-based approaches in the public and private sectors. The PCS spectrum was sold via a simultaneous multi-round auction, which forces bidders to compete for licenses individually even though they typically value certain combinations. This exposes bidders to risk when they bid aggressively for a desired combination but end up winning an inferior subset. Foreseeing this possibility, bidders may act cautiously with adverse effects for revenue and efficiency. Combinatorial auctions allow for bids on combinations of licenses and thus hold the promise of improved performance. Recently, a number of countries worldwide have switched to the combinatorial clock auction to sell spectrum. This two-stage auction uses a core-selecting payment rule. The number of possible packages a bidder can submit grows exponentially with the number of licenses, which adds complexity to the auction. For larger auctions with dozens of licenses bidders cannot be expected to reveal all their valuations during such an auction. We analyze the impact of two main design choices on efficiency and revenue: simple "compact" bid languages versus complex "fully expressive" bid languages and simple "pay-as-bid" payment rules versus complex "core-selecting" payment rules. We consider these design choices both for ascending and sealed-bid formats. We find that simplicity of the bid language has a substantial positive impact on the auction's efficiency and simplicity of the payment rule has as a substantial positive impact on the auction's revenue. The currently popular combinatorial clock auction, which uses a complex bid language and payment rule, achieves the lowest efficiency and revenue among all treatment combinations.

1. Introduction

The 1994 sale of radio spectrum for "personal communication services" (PCS) marked a sharp change in policy by the US Federal Communications Commission (FCC). Before turning to auctions the FCC had allocated valuable spectrum on the basis of comparative hearings (also known as "beauty contests") and lotteries. Nobel laureate Ronald Coase long advocated that market-based mechanisms would improve the allocation of scarce spectrum resources, but his early insights were ignored for decades (Coase, 1959). The PCS auction raised over 600 million dollars for the US treasury and it was widely considered a

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success. Several authors discuss the advantages and disadvantages of auctions and beauty contests for allocating scarce spectrum (McMillan, 1995; Morris, 2005; Valletti, 2001). For example, some argue that financially strong bidders might have advantages over weaker bidders in an auction, while others argue that with efficient capital markets such differences should be less of a concern. Nowadays, spectrum is predominantly assigned by auction, both in the US and elsewhere (Gruenwald, 2001; Jain, 2001), and in this paper we focus on questions of auction design.

The simultaneous multi-round auction (SMRA) which was designed for the US FCC in the early 90s has been the standard auction format for selling spectrum worldwide for many years. It auctions multiple licenses for sale in parallel and uses simple activity rules which force bidders to be active from the start. Despite the simplicity of its rules there can be considerable strategic complexity in the SMRA when there are synergies between licenses that cover adjacent geographic regions or between licenses in different frequency bands. Bidders who compete aggressively for a certain combination of licenses risk being exposed when they end up winning an inferior subset at high prices. When bidders rationally anticipate this *exposure problem*, competition will be suppressed with adverse consequences for the auction's performance. The exposure problem has led auction designers to consider combinatorial auctions, which enable bidders to express their preferences for an entire set of licenses directly. In fact, the design of spectrum auctions is seen as a pivotal problem in multi-object auction design and successful solutions are a likely role-model for other public or private sector auctions such as transportation or industrial procurement.

Since 2008, the combinatorial clock auction (CCA) has been used by regulators in various countries such as the Austria, Australia, Canada, Denmark, Ireland, the Netherlands, and Switzerland to sell spectrum.[1] The CCA combines an ascending auction where individual license prices rise over time (clock phase) in response to excess demand, with a sealed-bid supplementary phase. In addition, the auction uses a complex activity rule to set incentives for bidders to bid actively from the start (Bichler, Shabalin, & Wolf, 2013). Unlike the SMRA, bidders can demand combinations of licenses as well as individual licenses.

Combinatorial auctions can employ different types of bid languages, such as OR and XOR languages. Both allow bidders to submit indivisible bids on packages. For example, if a bidder bids on packages $\{A, B\}$ and $\{C, D\}$, he would only be assigned one of the packages at most with an XOR language. With an OR language he might win both packages. This way, the number of different bids is reduced substantially. However, if a bidder only wants to win one of the two packages and not both, he cannot express this in a pure OR language. Actually, the OR language can only express superadditive valuations.

The CCA has employed an XOR bid language so far, but this comes at the price of high communication complexity.[2] With 30 licenses the number of possible combinations already exceeds a billion, which are far too many for bidders to express their values for.[3] This can lead to inefficiencies because the winner-determination algorithm allocates the spectrum as if missing bids for certain combinations reflect zero values for the bidders. Often the number of possible bids per bidder even has to be capped to a few hundred in order to keep the winner-determination problem feasible. In the bid data that was recently released by Ofcom for the CCA that was conducted in the UK in 2013 bidders submitted bids on between 8 and 62 packages in the supplementary round from 750 possible package bids considering the spectrum caps.[4] It is unlikely that bidders had a zero value for all the other packages.

In spectrum auctions it is typically common knowledge what combinations of licenses generate the most synergies.[5] In this paper, we study how the introduction of a simple bid language, tailored to capture the main synergies, affects the performance of multi-band spectrum auctions. Our bid language allows bidders to specify either-or bids on packages within a band (XOR) while bids for packages in different bands are considered additive (OR). This way, the number of possible bids is reduced substantially. Although elements of the bid language can be used in practice, we do not suggest there is a one-size-fits-all bid language. Rather, we want to understand the potential benefits of such an OR-of-XOR bid language over a fully expressive one. Interestingly, the design of compact bid languages has not been an issue in the design of spectrum auctions in different countries and a fully expressive XOR bid language has always been used for the CCA.

Besides the bid language, another defining feature of the CCA is the *core-selecting payment rule*. Theoretical considerations for this payment rule are based on the Vickrey–Clarke–Groves (VCG) mechanism, which has a simple dominant strategy for bidders to submit their valuations truthfully. The VCG mechanism, however, can lead to outcomes where the winners pay less then what losing bidders are willing to pay with their bids.

[1] A single stage combinatorial clock auction has been proposed in Porter, Rassenti, Roopnarine, and Smith (2003). Such a single-stage ascending clock auction format was used in Nigeria (Doyle & McShane, 2003), for example. In contrast, we discuss the two-stage combinatorial clock auction that has been used in spectrum auctions throughout the world in the past 5 years (Cramton, 2013).

[2] This is separate from the issue of computational complexity for the auction designer, i.e., how to determine which bids are winning, which is known to be an *NP*-hard computational problem. Nisan and Segal (2001) point out that for fully efficient allocations and general valuations the communication requirements grow exponentially.

[3] Spectrum auctions with dozens of licenses have been conducted in Austria, Australia, Switzerland, the Netherlands, Ireland, and the UK. For example, in the 2012 auction in the Netherlands, 41 spectrum licenses in the 800 MHz, 900 MHz and 1800 MHz bands were sold. Switzerland auctioned 61 licenses distributed over 11 bands in 2012. Canada used a CCA for 98 licenses in 2014. Although not all packages will have a value for bidders in such auctions, large national bidders will not be able to submit bids for all packages with positive value in auctions with these many items.

[4] http://stakeholders.ofcom.org.uk/spectrum/spectrum-awards/awards-archive/completed-awards/800mhz-2.6ghz/auction-data/

[5] For example, there is high complementarity within the 800 MHz band in most European auctions, where a package of two licenses often has much higher value than two times the value of a single license. For the new LTE mobile communication standard, telecom companies typically aim for four adjacent blocks of spectrum (i.e., 20 MHz) in higher bands to fully leverage the new standard.