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# Synergistic valuations and efficiency in spectrum auctions

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ABSTRACT

In spectrum auctions, bidders typically have synergistic values for combinations of licenses. This has been the key argument for the use of combinatorial auctions in the recent years. Considering synergistic valuations turns the allocation problem into a computationally hard optimization problem that generally cannot be approximated to a constant factor in polynomial time. Ascending auction designs such as the Simultaneous Multiple Round Auction (SMRA) and the single-stage or two-stage Combinatorial Clock Auction (CCA) can be seen as simple heuristic algorithms to solve this problem. Such heuristics do not necessarily compute the optimal solution, even if bidders are truthful. We study the average efficiency loss that can be attributed to the simplicity of the auction algorithm with different levels of synergies. Our simulations are based on realistic instances of bidder valuations we inferred from bid data from the 2014 Canadian 700 MHz auction. The goal of the paper is not to reproduce the results of the Canadian auction but rather to perform "out-of-sample" counterfactuals comparing SMRA and CCA under different synergy conditions when bidders maximize payoff in each round. With "linear" synergies, a bidder's marginal value for a license grows linearly with the total number of licenses won, while with the "extreme national" synergies, this marginal value is independent of the number of licenses won unless the bidder wins *all* licenses in a national package. We find that with the extreme national synergy model, the CCA is indeed more efficient than SMRA. However, for the more realistic case of linear synergies, SMRA outperforms various versions of CCA that have been implemented in the field including the one used in the Canadian 700 MHz auction. Overall, the efficiency loss of all ascending auction algorithms is small even with high synergies, which is remarkable given the simplicity of the algorithms.

## 1. Introduction

Radio spectrum is a key resource in the digital economy. Recognizing its enormous value for society, the US Federal Communication Commission (FCC) decided in 1994 to replace their bureaucratic process ("beauty contest") with a market-based approach to assign spectrum: the Simultaneous Multiple Round Auction (SMRA). Since then the SMRA has successfully been used by many regulators and has generated hundreds of billions of dollars worldwide. Despite this success, the SMRA has also led to a number of strategic problems for bidders. Telecom operators typically have preferences for certain packages of licenses. In the SMRA this leads to the so-called *exposure problem*: bidders who compete aggressively for a certain package risk ending up with only a subset, possibly paying more than what this subset is worth to them. The inability to express preferences for packages directly adds strategic complexity for bidders

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and is a source of inefficiency in the SMRA. The exposure problem that is inherent to item-by-item competition has stirred interest in combinatorial auctions, which allow bidders to submit preferences for combinations or packages directly. The design of combinatorial spectrum auctions has drawn significant attention from researchers from various fields including economics, game theory, operations research, and computer science, see e.g. Cramton, Shoham, and Steinberg (2006).

Combinatorial auctions have also drawn interest from regulators. For their 2008 700 MHz auction, the FCC decided to augment the SMRA with the possibility to bid on a national package. This simple combinatorial auction was based on the Hierarchical Package Bidding (HPB) format that had been designed and tested by Goeree and Holt (2010). In the same year, the British regulator Ofcom pioneered the Combinatorial Clock Auction (Cramton, 2008) and regulators world-wide have since followed their example by adopting different versions of the CCA. The single-stage CCA (Porter, Rassenti, Roopnarine, & Smith, 2003) is a simple ascending format where bidders can submit multiple package bids in each round and prices are increased on items for which there is excess demand. Variants of single-stage CCA have been used in Romania in 2012 and in Denmark in 2016. The single-stage CCA creates incentives for demand reduction (Ausubel, Cramton, Pycia, Rostek, & Weretka, 2014), a problem which the two-stage CCA tries to address. The two-stage CCA allows for only a single package bid in each round and adds a sealed-bid “shoot out” phase and a core-selecting payment rule (Cramton, 2013). Both phases are governed by a revealed-preference activity rule. The two-stage CCA has been used in many countries including Austria, Australia, Canada, Ireland, the Netherlands, Slovakia, Switzerland, and the UK (Bichler & Goeree, 2017; Cave & Nicholls, 2017; Mochon & Saez, 2017).

One takeaway message from the recent literature is that the design of spectrum auctions is still a topic of intense debate. Another is that it requires different approaches – theory, laboratory experiments, and simulations – to understand the properties of alternative formats. Mechanism design theory has identified the unique efficient auction in which bidding truthfully is a (weakly) dominant strategy so that bidders do not require information about their rivals' valuations. Despite its desirable features, the Vickrey-Clarke-Groves (VCG) mechanism is rarely used in the field for various practical reasons (Ausubel & Milgrom, 2006, ch. 1). Bayesian-Nash implementation allows for a broader class of auction formats but imposes a strong common-prior assumption. Moreover, recent game-theoretical models of spectrum auction formats typically make simplifying assumptions about bidders’ valuations (Goeree & Lien, 2014), focus on small environments with a few items and players (Levin & Skrzypacz, 2016), or assume complete information to highlight strategic problems (Janssen & Karamychev, 2016). Laboratory experiments provide valuable insights as well, e.g. Goeree and Holt (2010), but the size of the markets that can be organized in an economic experiment is typically limited. And, like in theoretical analyses, experimental designs often ignore or simplify complicated institutional details (e.g. activity rules or spectrum caps).

In contrast, simulations allow one to analyze realistic market sizes and to take institutional details into account. As such they can provide complementary insights (Consiglio & Russino, 2007). Interestingly, there are no published simulation studies about spectrum auction markets that we are aware of, even though simulations are regularly used by consultants and telecoms to explore different bidding strategies.

### *1.1. Auctions as algorithms*

Spectrum auctions can be seen as large games with many bidders, licenses, and additional rules such as spectrum caps and activity rules. For example, the 2014 Canadian 700 MHz auction allowed bidders to bid on 18 packages in 14 regions leading to $18^{14}$ possible packages. In large games like this, bidders need a lot of information about competitors to bid strategically, and one might argue that strategic manipulation is less of a concern. But even if we ignore strategic bidding, it is far from obvious that auctions yield efficient outcomes. It is well-known that the allocation problem in a combinatorial auction where bidders have preferences for combinations of licenses is an NP-hard optimization problem (Cramton et al., 2006). The SMRA and different versions of the CCA can be interpreted as algorithms to solve this problem, and it is important to understand the approximation ratios of these algorithms (Domowitz & Wang, 1994). It is unclear whether to expect efficient outcomes even when bidders bid straightforwardly in each round of the auction.

Theoretical results on the allocation problem in combinatorial auctions are not encouraging. There is no polynomial-time algorithm that guarantees an approximate solution to the winner determination problem within a factor of $l^{1-\varepsilon}$ from the optimal allocation, where $l$ is the number of submitted bids and $\varepsilon$ a small number (Pekec & Rothkopf, 2003). The problem is APX-hard and the worst-case approximation ratio of any polynomial-time algorithm for the allocation problem in combinatorial auctions is in$O(\sqrt{m})$, where $m$ is the number of objects to be sold. In large spectrum auctions with many licenses such as the Canadian auction in 2014, this lower bound on efficiency is obviously very low[1] and provides no practical guidance. There are also results on the worst-case efficiency of the single-stage CCA with bidders who truthfully reveal their preferences (i.e., bid straightforward) in each round. This can also be seen as an algorithm to solve the allocation problem. Unfortunately, the worst-case approximation ratio can be $2 / (m + 1)$ with $m$ being the number of licenses (Bichler, Shabalin, & Ziegler, 2013b).

Worst-case bounds might be too pessimistic, and it is interesting to understand the average-case approximation ratio to the fully efficient solution of different auction types based on realistic problem instances. Numerical experiments are widely used in operations research and computer science to analyze the average-case solution quality of an algorithm, and they help to understand aspects of the algorithm that do not lend themselves to theoretical analysis or lab experiments. In particular, we want to study the average-case efficiency of different auction algorithms under the assumption of straightforward bidding. This provides an estimate of the efficiency that can be achieved by the auction algorithms that are commonly employed in the field *for realistic market sizes and considering all*

[1] $\sqrt{18*14} = 15.87$, such that the worst-case approximation of any polynomial-time algorithm might be $OPT/15.87$, where $OPT$ is the optimal solution to the allocation problem.