Handbook of Spectrum Auction Design

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In the past two decades, telecommunications has turned into a highly competitive industry where companies are competing to buy valuable spectrum. Following the successful Personal Communications Services (PCS) Auction conducted by the US Federal Communications Commission in 1994, auctions have replaced traditional ways of allocating valuable radio spectrum such as comparative hearings (sometimes referred to as "beauty contests"), or lotteries. In a spectrum auction a government uses an auction to sell the licenses to transmit signals over specific bands of the electromagnetic spectrum and to assign scarce spectrum resources.

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 allocation of spectrum licenses for several years provides strong investment incentives for the carriers. They shape the mobile telephony market in a country and have significant impact on the prices paid by and the service provided to end consumers.

The PCS auction was organized as a simultaneous multi-round auction (SMRA), a simple but flexible format to sell multiple objects in parallel and has many advantages. This auction format allows bidders to compete for licenses individually even though they typically value certain combinations. Unfortunately, SMRA 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. Spectrum auction design has seen several innovations recently such as the single-stage and the two-stage combinatorial clock auction, hierarchical package bidding, or sealed-bid combinatorial auctions. Combinatorial auctions allow bidders to express complementary valuations for packages of spectrum, however, they also lead to new design challenges such as the computational hardness of the allocation problem, or the combinatorial growth in the number of package bids in some auction formats.

The motivation for this edited volume came from discussions with regulators, consultants, and telecoms who were asking for literature on recent trends in spectrum auction design. Spectrum auctions are being conducted regularly across the world, and apart from academics and students in the various fields, practitioners want to get an overview of various developments in this field.

More generally speaking, the contributions in this book deal with resource allocation problems involving hard computational allocation problems, and strategic market participants. These questions are fundamental to computer science, economics, and operations research alike. Actually, combinatorial auctions are only possible nowadays due to the substantial advances in

combinatorial optimization in the past decades. These questions are not specific to spectrum auction design.

While we focus on spectrum sales, the questions raised are clearly beyond this application only. Multi-object markets of this sort can be found in industrial procurement, logistics, the sale of pollution permits, in day-ahead energy markets, or the sale of TV ad slots, to name just a few. Therefore, successful auction designs for spectrum markets are a likely role model for other domains as well.

Spectrum auction design is a central subfield of *market design*, an engineering-oriented field at the intersection of computer science, economics, and the management sciences. Market design uses economic theory, mathematical optimization, systems design, experiments, and empirical analysis to design market rules and institutions. Market design asks how the design of the rules and regulations of a market affects the functioning and outcomes of that market. This field has been honored with the 2012 Nobel Price in Economic Sciences for Alvin Roth and Lloyd Shapley.

The volume is organized in six parts. Part I focuses on the Simultaneous Multi-Round Auction, Part II on the Combinatorial Clock Auction, and Part III on alternative auction formats. Part IV summarizes experimental comparisons of different auction formats in the lab. Part V provides experiences and strategies of bidders in different auction formats, and Part VI includes contributions on secondary spectrum markets and exchanges.

Part I: The Simultaneous Multi-Round Auction

TBD: EXTEND

The Simultaneous Multi-Round Auction (SMRA) has been used to allocate spectrum worldwide for more than 20 years. This Chapter summarizes key contributions on the SMRA. It includes a pivotal overview paper by Paul Milgrom (Chapter 1), a game-theoretical analysis by Goeree and Lien (Chapter 2), as well as analyses of auctions in the field by Cramton (Chapter 3), and by Fox and Bajari (Chapter 4).

Part II: The Combinatorial Clock Auction Formats

The Combinatorial Clock Auction (CCA) describes a family of different but related designs, which was used world-wide since 2008. Chapter 5 describes a one-stage ascending clock auction in a paper by Porter, Rassenti, Roopnarine, and Smith. The first two-stage CCA design is outlined in Chapter 6 by Ausubel, Cramton, and Milgrom. In Chapter 7 Ausubel and Baranov provide a accessible guide to the CCA as it is used world-wide nowadays. Cramton discusses various properties and the design rationale in Chapter 8, while Ausubel and Baranov summarize differences in successive versions of the CCA in Chapter 9. Day and Cramton treat computational issues about the quadratic core-selecting payment rule used in the two-stage CCA in Chapter 10, and Day and Milgrom analyze this payment rule game-theoretically in Chapter 11. In Chapter 12, Erdil and Klemperer provide alternatives to the quadratic core-selecting payment rule.

Chapter 13 provides a Bayesian Nash equilibrium analysis of the broader class of core-selecting auctions assuming risk-neutral bidders and shows that no core-selecting auction can be in the core with respect to the true valuations if the Vickrey auction is not in the core. Guler, Bichler, and Petrakis (Chapter 14) show that the result extends to arbitrarily risk-averse bidders, although risk aversion can reduce the scope of inefficient equilibria. Janssen and Karamychev

analyze the impact of budget constraints on the CCA in Chapter 15, and Kroemer, Bichler, and Goetzendorff analyze bidding behavior in the CCA based on bid data from the field in Chapter 16.

Part III: Alternative Auction Designs

SMRA and the CCA both exhibit advantages and disadvantages, but they are not the only auction formats for single-sided multi-object auctions. Part III of this edited volume summarizes alternative auction designs. Some of them have been evaluated by regulators, some also been used for spectrum sales or other applications. In Chapter 17 Kwasnica, Ledyard, Porter and DeMartini introduce ascending combinatorial auctions with pseudo-dual linear and anonymous prices. Such designs have been analyzed for the sale of spectrum licenses and used in industrial procurement. Chapter 18 by Goeree and Holt describes Hierarchical Package Bidding (HPB), an auction format, which has been used by the US Federal Communications Commission to sell spectrum licenses.

Milgrom describes an auction format for substitutable preferences in Chapter 19, which is related to a design outlined by Klemperer in Chapter 20. This product-mix auction has been used to auction loans of funds secured against different varieties of collateral. Plot, Lee, and Maron introduce a continuous (not round-based) combinatorial auction format which has been used in field applications in Chapter 21. The original design of a combinatorial auction for the allocation of airport time slot by Rassenti, Smith, and Bulfin is described in Chapter 22. Finally, Bichler, Hao, and Adomavicius introduce a pricing rule to overcome the coordination problem that bidders face in larger ascending combinatorial auctions with exponentially many possible package bids.

Part IV: Experimental Comparisons of Auction Designs

Laboratory experiments have been recognized as important complements to game-theoretical analyses of auctions. They are particularly important for multi-object auctions, because game-theoretical models often need to make simplifying assumptions and human bidder behavior can deviate significantly from normative theoretical models. The Chapters in Part IV provide results of experiments, which aimed at a comparison of different auction formats.

Ledyard, Porter, and Rangel (Chapter 24) as well as Plott (Chapter 25) describe initial experiments to compare SMRA against sequential and combinatorial auctions. Brunner, Goeree, Holt, and Ledyard compare SMRA to auction formats using pseudo-dual linear and anonymous prices and a single-stage CCA in Chapter 26. With high complementarities in the valuations the combinatorial auction formats achieved higher efficiency than SMRA. Scheffel, Ziegler, and Bichler compare HPB with the single-stage CCA, and an auction with pseudo-dual linear prices in Chapter 27. Both, the CCA and HPB achieved high efficiency and revenue, but the package selection heuristics of bidders have a negative impact on efficiency in all combinatorial auction formats.

Chapter 28 by Bichler, Shabalin, and Wolf reports the first experiments to compare the two-stage CCA with SMRA in larger auctions with more licenses based on realistic spectrum band plans. The two-stage CCA achieved lower efficiency than SMRA in particular in multi-band auctions, which is partly due to the fully enumerative bid language used in the two-stage CCA and the fact that bidders can only submit subsets of the exponentially many packages with positive value. Chapter 29 by Bichler, Goeree, Mayer, and Shabalin then address the problem

with compact bid languages and show that combinatorial auctions with compact bid languages, where bidders can specify their preferences succinctly, have a significant positive impact on efficiency.

Part V: The Bidders' Perspective

Analytical models and lab experiments typically require some simplifications. The strategic challenges and problems of bidders are often beyond what can be modeled or analyzed in the lab experimentally. Part V covers reports of colleagues, who consulted in spectrum auctions shedding light on additional aspects which are important in the field.

In Chapter 30 Bulow, Levin, and Milgrom discuss bidding strategies in an FCC's Advanced Wireless Service auction leveraging information about other market participants and their budget revealed throughout the auction. Also Salant discusses bidding strategies in an SMRA with regional licenses in Chapter 31. Chapter 32 by Gretschko, Knapek, and Wambach, Chapter 33 by McKenzie and Fookes, and Chapter 34 by Marsden and Sorensen then focus on various strategic problems in the two-stage CCA.

Part VI: Secondary Markets and Exchanges

The move of regulators to use markets to allocate spectrum rights through auctions in the mid-1990s is widely considered a success. Yet regardless of how efficiently initial rights are allocated, changing supply and demand conditions mean that initial allocations can quickly become inefficient. Well-functioning secondary markets can ensure that spectrum can shift to new, more efficient uses. Such secondary markets might also be organized as a centralized market, which allows to better address interference constraints. Part VI discusses related ideas.

Berry, Honig, and Vohra provide a discussion of challenges and implications of secondary spectrum markets in Chapter 35. Chapter 36 by Milgrom and Segal describes the remarkable design of the US incentive auction in 2016, a large two-sided spectrum auction market allowing TV broadcasters to sell and telecoms to buy spectrum licenses. The allocation problem in this auction is a computationally hard problem discussed in a contribution by Frchette, Newman and Leyton-Brown in Chapter 37. Spectrum auction markets among telecommunication providers will require some support for package bids. Combinatorial exchanges are in their infancy, but we provide two examples of exchange designs in Chapters 38 and 39. Lubin, Parkes, Shneidman, Lahaie, Cavallo, and Juda propose an expressive iterative combinatorial exchange design in Chapter 38. Ledyard and Goeree describe a combinatorial call market for pollution permits in Chapter 39. Such designs provide valuable ideas for future spectrum markets.

The book will conclude with an outlook chapter discussing current challenges in the design of spectrum auctions. We would like to thank all contributors and the University of Technology Sydney for their support in organizing this edited volume and hope that it provides useful for regulators, bidders, and academics in this dynamic field of market design.