Preface

The 1994 sales of spectrum for "personal communication services" (PCS) marked a sharp change in policy by the US Federal Communications Commission (FCC), which had allocated spectrum for free until then. The PCS auction was designed by Stanford professors Paul Milgrom and Robert Wilson.[1] The July auction with just ten licenses raised over $600 million while the December auction raised more than $7 billion, breaking all records for the sale of public assets in the US and leading the *New York Times* to hail it as "the greatest auction ever." Substantial revenues are an obvious benefit but even more important is the fact that the PCS auction allocated this valuable public asset efficiently. By forcing firms "to put their money where their mouths are" the PCS auction selected firms that could utilize spectrum the best – to the greater benefit of society. Milgrom and Wilson's design has since been adopted by many regulators and has generated hundreds of billions of dollars for treasuries worldwide.

The PCS auction was organized as a simultaneous multiple-round auction (SMRA), which is also known as a simultaneous ascending auction (SAA). The SMRA is a simple but flexible format to sell multiple licenses in parallel. Despite the simplicity of its rules, the SMRA may create strategic difficulties for bidders interested in acquiring combinations of licenses. Since licenses have to be won one-by-one in the SMRA, bidders who compete aggressively for a desired combination risk winning an inferior subset at high prices. This is known as the *exposure problem*. Foreseeing the possibility of being exposed, bidders may act cautiously with adverse effects for revenue and efficiency.

Combinatorial auctions solve the exposure problem by allowing for bids on combinations of licenses. While this feature has the potential to improve efficiency, it also leads 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. Spectrum auction design has seen several recent innovations such as the single-stage and two-stage combinatorial clock auction (CCA), hierarchical package bidding (HPB), or sealed-bid combinatorial auctions.

[1] A closely related format that used a different stopping rule was proposed by Preston McAfee.

The motivation for this edited volume came from discussions with regulators, consultants, and telecom operators who were asking for literature on recent trends in spectrum auction design. High-stakes spectrum auctions are being conducted regularly across the world, and just like academics, practitioners would like to get an overview of the various developments in this field. The need for an edited volume that takes stock of the rapid developments in this field is illustrated, for instance, by the "Market-Design Experiments" chapter of the recent *Second Handbook of Experimental Economics* (2016). In this chapter, Al Roth, who received the 2012 Nobel Prize for his work on improving matching institutions, writes:

> "In summary, if I had written this section on FCC auctions in early 2008, it would have been tempting to conclude on a triumphant note: after years of experiments promoting package bidding, the FCC had finally implemented a limited version of it. In view of the subsequent return to auctions without package bidding, a more sober assessment may be called for."

It just goes to show how *the times they are a-changin'*. In retrospect the year 2008 is a turning point for combinatorial auction design, in terms of practical application and fundamental research. That year, the FCC successfully applied the hierarchical package bidding (HPB) auction to sell their 700MHz spectrum, resulting in record revenues of close to $19 billion. At the same time, regulators around the globe decided to substitute away from the SMRA and employ a combinatorial clock auction (CCA) or other combinatorial formats (e.g. Australia, Austria, Canada, Denmark, Montenegro, the Netherlands, Ireland, Slovenia, Switzerland, and the UK). Depending on the type of spectrum being sold the SMRA is still being used, as Roth notes, but the vast majority of spectrum auctions conducted since 2008 have allowed for combinatorial bidding. Moreover, combinatorial spectrum auction design has since blossomed into a prime example of innovative, impactful, and interdisciplinary research as attested by the contributions to this *Handbook*.

Besides spectrum auctions, the contributions to this book deal with resource allocation problems involving hard computational allocation problems and strategic market participants. These questions are fundamental to computer science, economics, operations research, and the

management sciences alike. Actually, combinatorial auctions are only possible nowadays due to the substantial advances in combinatorial optimization in the past decades. While we focus on spectrum sales, the questions raised are clearly not restricted to this application. 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. Successful auction designs for spectrum markets are a likely role model for other domains as well.

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 designs, and Part VI includes contributions on secondary spectrum markets and exchanges.

Part I: The Simultaneous Multi-Round Auction

The Simultaneous Multi-Round Auction (SMRA) is a beautifully simple generalization of the English auction to multiple licenses. All licenses are sold at the same time, each with a price associated with it, and the bidders can bid on any one of the licenses. The auction proceeds in rounds, which is a specific period of time in which all bidders can submit bids. After the round is closed, the auctioneer discloses provisional winners and current license prices, which equal the highest bids submitted for the licenses. The bidding continues until no bidder is willing to raise the bid on any of the licenses any more. In other words, if in one round no new bids are placed then the auction ends with each bidder winning the licenses on which he has the high bid, and pays the bid for any license won.

The SMRA has successfully been used to allocate spectrum for more than two decades raising hundreds of billions of dollars for Treasuries worldwide. Part I summarizes key contributions on the SMRA. It includes the seminal overview paper by Paul Milgrom (chapter 1), a game-theoretical analysis by Goeree and Lien (chapter 2), as well as empirical analyses by Cramton (chapter 3) and Fox and Bajari (chapter 4).

Part II: The Combinatorial Clock Auction Designs

The Combinatorial Clock Auction (CCA) refers to a family of different but related designs, which were 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. Cramton discusses various properties and the design rationale in chapter 7, while in chapter 8 Ausubel and Baranov provide an accessible guide to the CCA as it is used world-wide nowadays. In chapter 9 Ausubel and Baranov summarize differences in successive versions of the CCA. 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 the core-selecting 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. Levin and Skrzypacz provide a game-theoretical analysis of the specifics of the CCA and show that there are multiple equilibria in chapter 15. Janssen, Karamychev, and Kasberger analyze the impact of budget constraints on the CCA in chapter 16. Finally, Kroemer, Bichler, and Goetzendorff analyze bidding behavior in the CCA based on bid data from the field in chapter 17.

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 summa-

rizes alternative auction designs. Some of them have been evaluated by regulators, some also been used for spectrum sales or other applications. The original design of a combinatorial auction for the allocation of airport time slot by Rassenti, Smith, and Bulfin is described in chapter 18. In chapter 19 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 20 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 21, which is related to a design outlined by Klemperer in chapter 22. 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 23, and Bichler, Hao, and Adomavicius introduce a pricing rule to address the coordination problem that bidders face in larger ascending combinatorial auctions with exponentially many possible package bids in chapter 24.

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 25) as well as Plott (chapter 26) 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 27. 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 28. Both, the CCA and HPB achieved high efficiency and revenue, but the package selection heuristics of bidders had a negative impact on efficiency in all combinatorial auction formats.

Chapter 29 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 30 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 31 Bulow, Levin, and Milgrom discuss bidding strategies in a simultaneous ascending auction organized by the US Federal Communications Commission 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 32. Chapter 33 by Gretschko, Knapek, and Wambach, chapter 34 by Marsden and Sorensen, and Chapter 35 by Fookes and McKenzie 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 technical or strategic allocation constraints. Part VI discusses related ideas.

Berry, Honig, and Vohra provide a discussion of challenges and implications of secondary spectrum markets in chapter 36. Chapter 37 by Milgrom and Segal describes the remarkable design of the US incentive auction in 2016-2017, 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 Fréchette, Newman and Leyton-Brown in chapter 38. 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 39 and 40. Lubin, Juda, Cavallo, Lahaie, Shneidman, and Parkes propose an expressive iterative combinatorial exchange design in chapter 39. Fine, Ishikida, Goeree and Ledyard describe a combinatorial call market for pollution permits in chapter 40. Such designs provide valuable ideas for future spectrum markets.

The book ends with an outlook chapter discussing current challenges in the design of spectrum auctions.

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