# 1 Introduction

In this introductory chapter, we present an overview of the history of auctions. We then present critical issues and challenges of the current and future computer networks. Auctions can be used as effective tools to address these issues and challenges. We also discuss motivations for and significance of the use of auctions in the computer networks. Finally, we present the objectives, organization, timeliness, and potential audience of this book.

## 1.1 A Brief Overview of the History of Auctions

Auction theory is an applied branch of economics that deals with how people act in auction markets and researches the properties of auction markets. The word "auction" is derived from the Latin word *augeō*, which means "an increase of price" [1]. Auctions have been used for thousands of years for the sale of a variety of objects. In particular, around 500 BC, auctions of women for marriage were conducted in ancient Babylon [1]. During the Roman Empire, auctions were often used by Roman soldiers for trading spoils of war, such as slaves, after military victory. The Romans also used auctions to liquidate the assets of debtors whose property had been confiscated [2]. One infamous auction during the Roman Empire was described by Edward Gibbon in his *Decline and Fall of the Roman Empire* (1776). According to his account, when the Praetorian Guard killed the Roman emperor Pertinax in AD 193, an auction was used to sell the title of Roman emperor to the highest bidder [3]. The winner was a wealthy senator, Didius Julianus.

During the seventeenth and eighteenth centuries, the candle auction, a variation on the typical English auction, was commonly used in England for trading goods and leaseholds. In the candle auction, the end of the auction was signaled by the expiration of a candle flame. This process was intended to ensure that no buyer could know exactly when the auction would end and make a last-second bid.

Auctions of fruits and vegetables became established in the Netherlands around 1880. The farmers' efforts grew to include a vast system of markets for horticultural goods, associated especially with tulips. At the same time, the selling of fish by auction became important in Germany. One main reason for the use of auctions in this case is the fact that fish can be sold fast.

In the modern era, auctions have been used by governments to allocate items for which it is difficult to determine market prices. The items are typically public goods and assets such as electricity, wood, airport time slots, industrial equipment, real estate, bus lines, emission rights, and the use of electromagnetic spectrum. In particular, auctions of rights (i.e., licenses) to use the electromagnetic spectrum for wireless communications are a worldwide phenomenon. In the spectrum auction, the government uses an auction system to assign scarce spectrum resources to parties. With a well-designed auction, the spectrum resources are allocated efficiently to the parties that value them the most, and the government gains revenue. For example, since July 1994, the Federal Communications Commission (FCC), an independent agency of the US government, has raised over $60 billion for the US Treasury by conducting 87 spectrum auctions [4]. Also, in 2000, the Radiocommunications Agency of the UK government (now Ofcom) raised £22.5 billion from an auction of five licenses for radio spectrum to support the 3G mobile telephony standard [5]. In 2018, the Exchequer (i.e., the British government department) received the total of £1.3 billion from the spectrum auction for the future 5G mobile services [6].

In recent years, the rapid growth in the Internet has facilitated conducting auctions. In particular, the Internet facilitates online activities, such as bidding and payment, between buyers and sellers in different locations or geographical areas. This further reduces transaction cost. *eBay* is one example of a company that uses the Internet for auctions. This auction house and business entity directly facilitates the sale–purchase of items between sellers and buyers. In particular, online buyers search for the desired item and then make bids on the item through auctions, and the bidder with the highest bid wins the item. In January 2019, eBay ranked as the 38th most popular website in the world and the 10th most popular website in the United States [7].

With the development of auction theory and experimental research, more sophisticated auction designs have appeared that enable auctions to be applied to various problems in dynamic, uncertain, and complicated environments.

## 1.2 Auction Theory in Computer Networks

The advancement of computing and telecommunication technologies will enable modern computer networks to become ubiquitous due to the huge demand of pervasive applications. The convergence of cloud computing, mobile networks, and media will allow users to communicate with each other and access any content anytime and anywhere. Modern computer networks will serve a massive number of users and applications with various services with diverse requirements such as high-speed access, real-time Internet games, interactive media, video-on-demand, edge computing, smart homes, intelligent transportation, and autonomous systems. Also, modern computer networks are expected to bring huge new business opportunities for stakeholders including content/service providers, network operators, and infrastructure providers. However, there are many challenges to be addressed to realize the promise of modern computer networks. These challenges come from (i) the heterogeneity and dense deployment of network devices; (ii) the heterogeneous computing and networking

resources; (iii) the large degree of uncertainty of the consumer demand for network resources and services; and especially (iv) the rationality and self-interested behaviors of network entities, including both, users and stakeholders. Therefore, one critical issue is devising distributed, dynamic, and adaptive algorithms for (i) ensuring a robust network operation over time-varying and heterogeneous environments and (ii) optimizing decisions on services and resources allocation/usage of all network entities.

Auction theory, also known as a subfield of economics and business management, has been introduced as a tool for computer network design, protocol optimization, and resource allocation. The main reasons are as follows.

- Auctions model interactions among network entities, especially from the economic perspective. This economic aspect of the system becomes more and more important as the network entities are self-interested in their benefits obtained by supplying or consuming network resources and services.
- Auctions provide an incentive mechanism that is important to determine the values and specifically the prices of network resources and services. Auction emerges as a bridge between system design and pricing from engineering and economic perspectives, respectively. The convergence of two fields in computer networks is a nascent approach that can show many advantages over using a classical system or economic solution alone. Therefore, it is inherently suitable for modern computer networks, which consist of multiple autonomous entities.
- Auctions can support different objectives, ranging from revenue maximization for the auctioneer to social welfare maximization for the entities, and provide various desired properties, such as truthfulness, economic efficiency, and individual rationality. This makes designed mechanisms attractive to network entities.
- Auctions allow the allocation of bundles of diverse resources, which satisfies dynamic demands and improves the resource utilization in heterogeneous environments.

As a result, auctions have been explored as means to solve various problems in modern computer networks including the Internet of Things (IoT), cloud networking, and 5G wireless networks. Emerging problems consist of data aggregation, task allocation, user association, interference management, cloud and network resource allocation, wireless caching, and mobile data offloading. More importantly, auctions have been introduced as an effective solution to address network security issues. Practitioners have shown that designing the modern computer networks with self-interested entities can be easily implemented by using auction theory.

## 1.3 Organization and Timeliness of This Book

### 1.3.1 Organization

Providing a comprehensive introduction to the basics of auction theory and giving example applications of auction theory for the design of modern and emerging computer networks are the main objectives of this book. Specifically, the first objective is to

provide a general introduction to modern computer networks and the most recent developments related to these networks. The second objective is to introduce different auction theoretic models and techniques as well as to present applications of the state-of-the-art auction mechanisms for handling a variety of problems in computer networks. The choices of appropriate techniques for designing computer networks are important. Therefore, we present fundamentals of auction theoretic techniques and then present the developments of these techniques for design, analysis, and optimization of computer networks. To achieve these objectives, this book is organized as follows:

- **Overview of Modern Computer Networks:** Chapter 2 introduces the background, the fundamentals, and the emerging issues of modern computer networks. We first provide definitions of IoT and describe the general architecture, resources, and services of IoT. Important components of IoT, including wireless sensor networks and mobile crowdsensing networks, are further discussed. Second, we introduce cloud networking models that aim to provide on-demand data storage, computing, and network resources to cloud clients/users. The cloud networking models include cloud data center networking, mobile cloud networking, and edge computing. Furthermore, we present the cloud-based video-on-demand system that is known to be a new video content delivery model in the development of cloud networking. Third, we provide an overview of key technologies, such as massive multiple-input and multiple-output (MIMO) and millimeter wave (mmWave) communications, that may potentially be deployed in the 5G wireless networks. Finally, we discuss several emerging issues in the computer networks, including data aggregation, task allocation, user association, interference management, wireless caching, mobile data offloading, and security. In particular, we describe security issues in wireless networks involving eavesdropping attacks, denial-of-service (DoS) attacks, information security issues, and malicious behaviors of users. The motivations of using pricing models as well as auctions for each issue are highlighted.
- **Mechanism Design and Auction Theory in Computer Networks:** Chapter 3 introduces mechanism design and auction theory. Mechanism design aims to determine allocation and payment rules toward objectives or desired objectives. In this chapter, we first define the mechanism as well as the allocation and payment rules of the mechanism, design. The mechanism design task is generally a complicated search problem. Thus, we introduce the revelation principle that can be used for facilitating the mechanism design task. The required properties of the mechanism, such as incentive compatibility, individual rationality, economic efficiency, and budget balance, are also presented. We further discuss optimal mechanisms in terms of social surplus maximization and profit maximization. After that, we introduce the basics of the auction theory and present the motivations as well as the significance of applying auctions to computer networks.
- **Open-Cry Auction:** Open-cry auctions are the most conventional auctions. Chapter 4 discusses two types of open-cry auctions, the English and Dutch auctions, and presents their applications in computer networks. Specifically,

we first introduce the theory of the English auction and demonstrate how to obtain the equilibrium strategies in this type of auction. Second, we discuss the application of the English auction to the spectrum leasing of cognitive radio in the 5G wireless networks. Third, we provide the definition and process of the Dutch auction. In particular, we introduce the revenue equivalence theorem that is used to determine the Nash equilibrium in the Dutch auction. Different from the English auction, the Nash equilibrium in the Dutch auction is the Bayesian Nash equilibrium; that is, a particular bidder determines its equilibrium strategy by knowing the distribution of values of other bidders rather than knowing their actual values. This is a common situation in computer networks where there is no centralized controller to maintain information about users. Fourth, we discuss the applications of the Dutch auction to emerging issues such as black hole attacks, relay selection, and channel allocation. We finally introduce the combination of English and Dutch auctions as a solution for some situations in which the auctioneer has no information about the market price of its item.

- **First-Price Sealed-Bid Auction:** Chapter 5 introduces a common type of *k*th-price sealed-bid auction, the first-price sealed-bid auction. In the first-price sealed-bid auction, buyers simultaneously submit their bids in sealed envelopes to the seller. The buyer with the highest bid is the winner and pays the seller the price that the buyer submits. In this chapter, we present the strategic analysis of bidders in the first-price sealed-bid auction. We further discuss how to find the equilibrium strategies of bidders in the auction. After that, we introduce the first-price sealed-bid reverse auction, which is a variation of the first-price sealed-bid auction. Finally, we discuss the applications of the first-price sealed-bid auction to address emerging issues in IoT.
- **Second-Price Sealed-Bid Auction:** Chapter 6 presents another type of *k*th-price sealed-bid auction, the second-price sealed-bid auction or Vickrey auction. Different from the first-price sealed-bid auction, the winner in the Vickrey auction pays the seller the second-highest bid. This chapter contains two main parts. The first part introduces the second-price sealed-bid auction and its application in computer networks. In particular, we provide a definition of the second-price sealed-bid auction and discuss the dominant strategy as well as the Nash equilibrium in this type of auction. Then, we compare the dominant strategy in the second-price sealed-bid auction and the equilibrium strategy in the English auction to show that the two auctions have the same truthful bidding strategy and can achieve the same revenue. To show the efficiency of the second-price sealed-bid auction, we present the applications of this auction for addressing important issues such as the task allocation in IoT, task scheduling in edge computing, and physical layer security in a mobile ad hoc network (MANET). The second part introduces a generalization of the second-price sealed-bid auction with multiple items, the Vickrey–Clarke–Groves (VCG) auction. We formally describe the VCG auction through an example from the computer networks' perspective. Considering some specific cases, we prove the dominant strategy in the VCG auction. Then, we provide examples to show how the VCG auction works.

- **Combinatorial Auction:** A combinatorial auction allows bidders to bid on combinations or packages of multiple items; it both satisfies dynamic demands and improves the resource utilization. Chapter 7 pursues our discussion by introducing the combinatorial auction and its applications in modern computer networks. We first introduce two types of items commonly used in the combinatorial auction, known as substitutable and complementary items. Then, we present types of bidding language, such as atomic bids, OR bids, and XOR bids, that allow bidders to succinctly encode or express common bids in the combinatorial auction. After that, we present the basic definition of the winner determination problem in the combinatorial auction. One of the most challenging aspects of the combinatorial auction is the high computational complexity required to solve the winner determination problem. To address this challenge, we present two iterative combinatorial auctions, the ascending proxy auction and the clock-proxy auction. Finally, we discuss how the combinatorial auction is used to address resource management issues in computer networks.
- **Double-Sided Auction:** Chapter 8 discusses the double-sided auction or double auction in modern computer networks. Different from the aforementioned auctions, the double sided-auction provides a mechanism for multiple buyers and multiple sellers. More specifically, the buyers and sellers first submit their bids and asks, respectively, to an auctioneer. Here, the auctioneer is an entity that conducts the auction. The auctioneer then matches asks from sellers and bids from buyers by assigning items from the sellers to the buyers and payments from the buyers to the sellers accordingly. In this chapter, we first describe the single-round double auction with two pricing policies, uniform pricing and discriminatory pricing. In addition, we show a well-known economic model, the supply and demand model, that works similarly to the single-round double auction. Some specific examples from computer networks are then given and analyzed to show how to determine the winners and the prices in the single-round double auction. The single-round double auction is considered to be the sealed-bid double auction in which the participants – that is, the buyers and the sellers – cannot learn the bidding strategy of their rivals and discover the real values of the resources. To address this issue, we introduce the continuous double auction, which allows the participants to trade the resources in multiple rounds. The applications of the double auction for emerging issues in computer networks are finally reviewed.
- **Other Auctions:** Chapter 9 introduces and discusses some special auctions. We first present the ascending clock auction, which has some similarities to the English auction. To understand how this auction works, we discuss the use of the ascending clock auction for improving the physical layer security in a cognitive wireless network. Then, we introduce the share auction, which has the low computational complexity and is typically used in markets with divisible goods. We next introduce the online auction, which allows the seller to make decisions about allocation and payments in real time. Finally, we introduce the waiting-line auction, which can be formulated as a non-cooperative game and its Nash equilibrium. The waiting-line auction is known as a non-money auction

in which the winners are determined based on waiting times submitted from the bidders rather than their bidding prices.

- **Optimal Auction Using Machine Learning:** The best way to design the optimal option is still an open issue. Chapter 10 introduces the design of optimal auctions using the deep learning technique. In particular, we first introduce the optimal auction design problems, the deep learning technique, and the motivations of the use of the deep learning technique for designing the optimal auctions. After that, we describe the neural network architectures that are used to derive the optimal multi-item auction and the Myerson auction. To demonstrate the efficiency of the deep learning–based auctions, we apply the auctions to resource management in a blockchain network.

In summary, this book constitutes a complete and comprehensive reference for auction theory and its applications in modern computer networks. Furthermore, owing to the aforementioned structure, which integrates the theory and the applications, this book is easy to follow and understand for general readers.

### 1.3.2 Timeliness of the Book

Recently, there has been tremendous interest in auction theory and its applications in the computer network research community. Auction and mechanism design has become a means of computer network design, protocol optimization, and resource allocation that takes not only system parameters but also economic implications into account. As such, there is an immediate need for references that provide comprehensive basics, background information, insightful analysis, and example applications of auction theory in computer networks. The references should be organized in such a way as to provide descriptions of theory, analytical derivation of models, and demonstration of real-world problems. The major reasons that this book is timely and impactful can be explained based on the following observations:

- *Promising economic-driven approach for next-generation Internet:* Recently, a number of new network services and applications have been introduced and become hugely popular, such as IoT, cloud computing, software-defined networking (SDN), and next-generation cellular networks. They are driving the consumer demand for network connections and services to an unprecedented level. Furthermore, with stringent quality of service (QoS) requirements, it becomes challenging for stakeholders, including content/service providers, network operators, and infrastructure providers, to deliver their services and manage their network resources by using traditional centralized system optimization approaches.

  The limitations of the system optimization approaches are as follows. First, the next generation networks and Internet involve multiple stakeholders that deploy their own services and resources in an uncoordinated way. They aim to achieve their various kinds of benefits, which may not be translated directly from system performance. Second, the different network resources and services are integrated to support customer demand and meet application requirements. Such

an integration and composition have to achieve not only system optimality, but also market efficiency. The latter cannot be directly incorporated in the traditional system optimization approaches. Third, all stakeholders in the next-generation networks and Internet make their decision rationally, motivated by interests and incentives. Moreover, the stakeholders do not know the value of their resources and services. System optimization approaches largely fail to capture rationality and self-interest nature of the network entities.

Alternatively, auction and (economic-driven) mechanism design has emerged as an alternative that offers many benefits:

- Including an economic incentive in network service and resource allocation: Traditional centralized system optimization approaches rely only on network performance factors such as throughput, delay, and loss. However, stakeholders in next-generation networks and the Internet are self-interested in maximizing their own benefits such as revenue and profit. Therefore, incentive mechanisms are required for them to reach an optimal service and resources allocation/utilization. Auctions provide a well-defined incentive structure and allocation method, and hence become very suitable tools.
- Determining the value and market prices of network resources and services: Service providers and users may not know the exact values of network services and resources. Auctions offer a method to derive the values of services and resources by allowing different entities to propose their values. The market prices, meaning the values accepted by all entities, are determined by a set of certain rules.
- Supporting open and objective resource and service allocation methods: Auctions provide standard procedures in network resource and service allocation. Stakeholders and users can optimize their decisions about resource and service usage based on the rules and criteria that are given and open in advance. Moreover, the resource and service allocation is publicly observable, promoting transparency and predictability of the system operations.
- Promoting efficient allocation and investment: Since the allocation and pricing rules in auctions are open and objective, they can be defined to achieve the maximum market efficiency. Moreover, auctions can take the cost and investment into account in the allocation to achieve such a goal.
- Incorporating public policy goals and other constraints: As the next-generation networks and Internet will be used as a platform for many commercial and social applications, public policies for network resource and service allocation – for example, for public safety – will be imposed. Moreover, to ensure fair share and competition of the stakeholders, constraints are imposed, such as to avoid collusion. Auctions can incorporate the policies and constraints in the mechanisms.
- More resilient outcomes: Different auctions can achieve desirable properties such as non-negative utility, efficient allocation, and profit/utility

maximization. These properties enable effective network resource and service allocation.
  - Rigorous mathematical tools: Auction theory has a long history. It contains rich analytical tools to investigate important characteristics of the systems and allocation. Moreover, auctions include many variants, such as single-item and multi-item auctions, single-sided and double-sided auctions, and combinatorial auctions, that can be applied with a variety of applications and scenarios.

- *Most existing auction theory books Focus on economics applications:* As auction theory has many benefits, a textbook that provides fundamentals and example applications will be useful to researchers and network engineers. However, the current books are mostly written to fit the economics and mathematics context. In consequence, researchers and engineers working in the computer networks area can find it difficult to comprehend and apply the theory to their work. These books use different terminology, contain many technical terms, and make a large number of domain-specific assumptions that are difficult to connect to physical network operations and resource/service management. Furthermore, developing auction models to address different issues in emerging computer networks by relying on standard textbooks from economics and mathematics fields is not straightforward. It requires multidisciplinary domain knowledge to achieve the system goals. This becomes more challenging as the network technology changes rapidly and quick solutions are needed. As a result, there is an urgent need for an auction textbook that provides content in the computer network context.
- *Emergence of network and Internet services:* As software-based networks become a major trend, a number of network services are emerging rapidly in which models that capture the system performance and economic incentive optimization are required. Some examples of such networks are:
  - IoT and wireless sensor networks, participatory sensing networks, and mobile crowdsensing networks, which provide data and information services, location-based services, and IoT security.
  - Network security services, which provide solutions for the security issues in wireless networks such as physical layer security, DoS attack prevention, and information security.
  - Cloud computing and networking, including cloud data center networking, mobile cloud networking, and edge computing, which provide cloud computing infrastructure and networking capabilities such as Network-as-a-Service (NaaS) and video-on-demand (VoD) services.
  - 5G networks with emerging technologies such as MIMO, mmWave communications, cloud-radio access networks, and heterogeneous networks that support a wide range of services including broadband access services, ultra-reliable communications, high user mobility, and massive IoTs.

This book is intended, primarily, for the following audiences:

- Graduate and senior undergraduate students interested in applying auction theory and developing the models for their dissertations, theses, and projects.
- Network engineers and software developers interested in studying and using new economic tools for network service and resource allocation.
- Economists interested in revenue optimization using auction theory in emerging network services and systems.
- Researchers interested in the state-of-the-art literature on auction theory for solving various issues in computer networks.

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