Auction Approaches for Resource Allocation in Wireless Systems: A Survey

Yang Zhang, Chonho Lee, Dusit Niyato, and Ping Wang

***Abstract*—As wireless systems evolve with new mobile technologies, they tend to become complicated in terms of architectures and managements. Auction theory, as a subfield of economics and business management, has been introduced to provide an interdisciplinary technology for radio resource allocation (e.g., subchannels, time slots, and transmit power levels) in the wireless systems. By using various auction approaches, such radio resources are efficiently allocated among users and providers of services in the systems. Participants (i.e., users and providers) of an auction have their own strategies that follow the incentives and rules brought by the auction. Auction methods are widely employed in areas such as cognitive radio, cellular networks, and wireless mesh networks. This paper gives a comprehensive survey of recent auction approaches (i.e., auction-based applications and mechanisms) applied in wireless and mobile systems. First, auction theory and different types of auction are introduced. The motivation of using auction in wireless systems is given. Then, the reviews of auction approaches applied in the single-hop and multi-hop wireless networks are provided. Finally, the open research issues are discussed.**

***Index Terms*—Radio resource management; Cognitive radio; Spectrum sharing; Mobile ad hoc network; Auction; Mechanism design.**

I. INTRODUCTION

WIRELESS and mobile technologies have been advancing fast recently. As the growth of wireless/mobile devices, applications and users, service providers need to provide emerging wireless services and employ new wireless architectures in the future, such as 3G/4G mobile network, cognitive radio and mobile cloud systems. The wireless environment will become more dynamic, distributed and heterogeneous, which brings new challenges in the designs and optimization of the radio resource usage. Traditional static methods are not capable of supporting the resource management in current and future wireless systems.

The complexity features make current wireless systems analogue to real markets, i.e., various participants in the system transacting commodities (e.g., information) under certain regulations. Therefore, economics and business management approaches [1] are recently employed to dynamically and efficiently manage radio resources of wireless systems. Auction [2] is one kind of such interdisciplinary methods used to solve issues in the radio resource management. The components of the wireless system can be categorized into three main groups so that auction models can be applied: buyers, sellers and auctioneers. Buyers are spectrum users who have net resource inflows by paying money. Sellers have net resource outflows and earn revenues. Auctioneers control and conduct auction processes. Auction models can be applied in both centralized and distributed systems, with users in systems knowing full, partial or none of knowledge about other users.

This paper presents a survey of auction-based applications and resource managements in wireless systems. The rest of this survey is organized as follows. In Section II, we provide an overview of auction theory in terms of the concepts, categorization and objectives. Section III explains motivations to use auction approaches in radio resource management. Section IV introduces specific design issues when applying auctions to wireless scenarios. Section V and Section VI present auction applications and approaches in single-hop networks (e.g., cognitive radio systems and cellular networks) and multi-hop networks (e.g., wireless mesh networks, wireless sensor networks (WSNs) and mobile ad hoc networks (MANETs)), respectively. Section VII discusses some open issues of auction enabled research in wireless systems. Finally, Section VIII concludes this paper.

II. OVERVIEW AND FUNDAMENTALS OF AUCTION THEORY

Auction is a process to buy/sell commodities and services, which has been well researched in both economics and engineering areas. Basic terminologies in auction theory can be stated as follows:

- *Bidder*: A bidder is the one who wants to buy commodities in auctions. In wireless systems, a bidder is usually a user who wants to buy radio resources to complete tasks of transferring data, the user compete for the resources with other users. We may use *buyer* and *user* as synonyms for “bidder” in this paper.
- *Seller*: A seller owns and wants to sell commodities. The commodities can be bandwidth, licenses of spectrum, and time slots. in radio resource auctions. Buyers and sellers are all auction players.
- *Auctioneer*: An auctioneer works as an intermediate agent who hosts and directs auction processes. In general, a seller can be an auctioneer itself. For example in wireless systems, a base station or an access point can conduct resource auctions by its auction controller.
- *Commodity*: An *auction commodity* (also known as an auction commodity) is the object traded between a buyer and a seller. Each commodity has a value at which the buyer/seller wants to buy/sell.
- *Valuation*: In general, valuation is monetary evaluation of assets. A buyer/seller has a reserved valuation on

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every lot of commodities. Different buyers and sellers may value commodities with different valuations (which might be higher or lower than the inherent valuations) depending on their preferences. A valuation can be *private* that buyers do not know the others' valuations, or *public* that is known to the others.

- *Price*: During an auction, a seller can submit an *ask*, indicating the asking price on the commodity to be sold. On the other hand, a buyer can submit a *bid*, indicating the bidding price for the requested commodity. A *hammer price* is settled by the auctioneer, indicating that the buyer and the seller will make a deal at that price. Generally, a buyer/seller will not accept a hammer price that is high/lower than its valuation.

Theoretically and practically, there are many kinds of auction designs. Some simple examples of categorization are as follows:

- *Forward or reverse*: A *forward auction* means buyers bid for commodities from seller(s), as shown in Fig. 1a. In a *reverse auction*, sellers compete for buyer(s)' patronizing, as in Fig. 1b.
- *Single-sided or double-sided*: In a *single-sided auction*, only buyer or seller takes bid/ask actions (Fig. 1a and Fig.1b), and both buyer and seller make bids and asks in a *double-sided auction* (Fig. 1c).
- *Open-cry or sealed-bid*: In an *open-cry auction*, buyers call out their bids, not afraid of others to know, and in a *sealed-bid auction*, buyers submit their bids secretly to the auctioneer(s) without others to know.
- *Single-unit or multi-unit*: Buyers in a *single-unit auction* can bid for one auction commodity at a time, but multiple commodities in a *multiple-unit auction*.

Besides those listed above, there are other ways to categorize auction designs in [2]. For the rest of this section, we introduce the details of auction types often used in wireless systems. The auctions mentioned below are summarized in Table I.

A. Conventional Auctions

- *English auction*: An English auction [3] works as an ascending-bid auction, i.e., the bidding price submitted by buyers will increase monotonically. Consider an English auction with a single auction commodity T. During the auction period, buyers submit their bids sequentially or simultaneously to the auctioneer (or the seller). The auction will terminate when no buyer bids a new higher price. Then, the buyer who offers the highest price finally wins the auction. When the auction commodity is sold, the hammer price p satisfies $v_0(T) \leq p \leq \max_{b_i \in B} G(b_i)$, where $v_0(T)$ is seller's valuation to the auction commodity T, i.e., the lowest price at which the seller can accept to sell it, B is the set of bidders, and $G(b_i)$ is buyer b_i's budget. The hammer price may not necessarily equal the winning buyer b_i's valuation $v_i(T)$. The price changes depending on the intensity of competition in the auction.
- *Dutch auction*: A Dutch auction [3] is a descending-bid auction. The seller firstly sets an initial ceiling price for the commodity, and decreases the price over time (e.g. per hour), until the price becomes zero. Once a buyer accepts the current price by placing a bid, the auction terminates. Then the winning buyer pays the final price and receives the commodity.

B. Sealed-bid Auctions

In a sealed-bid auction, buyers do not call out their prices. Instead, they privately submit bids to the auctioneer (or the seller) without knowing other buyers' bidding strategies.

- *k-th-price sealed-bid auction*: *First-price* and *second-price* sealed-bid auctions are the two most important sealed-bid auctions. In the first-price auction, the winner is the buyer b_i who submitted the highest price p_i. Then the winner must pay that highest price as payment. A second-price sealed-bid auction is also known as Vickrey auction [4]. In a Vickrey auction, the winner is still the buyer b_i with the highest bid p_i. However, the price that the winner must pay is the second highest bid $p_j = \max_{p \in P \setminus \{p_i\}} p$, where P is the set of all bids.
- *VCG auction*: A Vickrey-Clarke-Groves (VCG) auction [5], [6], [7] is a generalized Vickrey auction. The seller offers a set of M commodities for sale, i.e., $T = \{t_1, t_2, \ldots, t_M\}$, where t_i indicates the ith commodity to be sold. Let $B = \{b_1, b_2, \ldots, b_N\}$ denote a set of N buyers. Each buyer $b_i \in B$ offers a bid $v_i(T^{(b_i)})$, where $T^{(b_i)} = \{t_1^{(b_i)}, t_2^{(b_i)}, \ldots, t_M^{(b_i)}\}$ is the set of commodities that buyer b_i wants from the auctioneer. After collecting all buyers' bids, the auctioneer computes the optimal commodity allocation $A = \{T^{*(b_1)}, T^{*(b_2)}, \ldots, T^{*(b_N)}\}$ that maximizes the total revenue, where $T^{*(b_i)} = \{t_1^{*(b_i)}, t_2^{*(b_i)}, \ldots, t_M^{*(b_i)}\}$ is the set of allocated commodities to buyer b_i. The price that each buyer must pay is defined as $p_i = U_T^{B \setminus \{b_i\}} - \sum_{j \neq i} v_j(T^{*(b_j)})$, where $U_T^{B \setminus \{b_i\}}$ indicates the optimal seller's revenue as if b_i does not participate in the auction, and $\sum_{j \neq i} v_j(T^{*(b_j)})$ is the sum of buyers' valuations (except b_i) to the allocated commodities.

C. Reverse Auction and Double Auction

Auctions can also be categorized by two different points of view, a *seller-side* and a *buyer-side*. The auctions mentioned so far are all from seller's point of view. Here, we introduce auctions from buyer's point of view, and a general type of auction named double-sided auction.

- *Reverse auction*: Forward auctions are namely *seller-side auctions*, where buyers compete for the commodities from the seller. However, in a reverse auction [2], also named a *buyer-side auction*, sellers compete to sell auction commodities to buyers instead, as shown in Fig. 1b. Generally, if the forward auction is an ascending-bid auction, its corresponding reverse auction is a descending-bid auction, and vice versa. For example, in a reverse English auction with multiple sellers and a single buyer, the sellers submit asking prices decreasingly to attract the buyer. Whoever can sell at the lowest price becomes a winning seller, and charges the hammer price to the buyer.

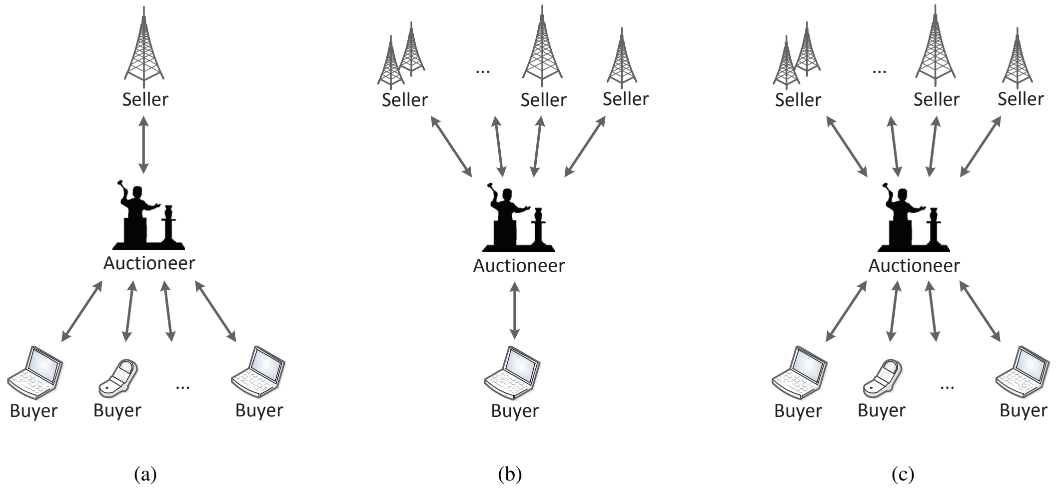


Fig. 1. Different types of auctions: (a) forward auction with a single seller; (b) reverse auction with a single buyer, (c) double auction. The arrows indicate transactions of commodities and money among auction players.

TABLE I
SUMMARY OF IMPORTANT AUCTIONS AND FEATURES.

Auction Type	Reference	Key Features and Descriptions	Suitable Scenarios
English	[3]	· Open-cry bidding process · Bidding price monotonically ascending	· Seller aims to maximize revenue
Dutch	[3]	· Open-cry bidding process · Available bidding prices quoted by seller · Bidding price monotonically descending	· Auctioning perishable commodities
Anglo-Dutch	[19]	· A dual-step auction · Mixture of English and Dutch auctions	· Multi-stage resource allocation process
k-th Sealed-bid	[3][4][5]	· Private bid process · Winning buyer pays the k-th highest price · Vickrey Auction when $k = 2$	· Widely applied in theoretical researches · Not practical due to computational complexity
VCG	[4][5][6][7]	· Generalized Vickrey Auction · Truthfulness guaranteed	· Widely applied in theoretical researches · Not practical due to computational complexity
Double	[8]	· Multiple sellers and multiple buyers · Both buyers and sellers make bids and asks	· Real world market with many sellers and buyers
Combinatorial	[13][14]	· Multiple heterogeneous auction commodities · Certain bundles of commodities are valued most	· Allocations of tightly coupled resources · E.g.: CPU, memory, storage and bandwidth resources
Waiting-line	[22]	· Buyers in front of the queue win the auction · Trade-offs between "queueing to win" and "waiting"	· Auction in a queueing system

- *Double auction*: A double auction [8] is a practical auction model that is widely used in real world markets, e.g., stock exchanges. In the double auction, both sellers and buyers submit their asks and bids, respectively. There is usually an auctioneer as a trading agent between the buyers and the sellers (e.g., in [9], [10], [11]), who decides the auction commodity allocation scheme and the hammer price (also known as a clearing price). Or else, there may be no centralized trading agent so that the sellers and buyers have to make deal directly (e.g., [12]). The double auction works as follows. The auctioneer collects asks and bids from sellers and buyers, respectively. Then, the auctioneer matches those asks and bids by allocating auction commodities from the sellers to the buyers, as well as payments from the buyers to the sellers accordingly. This matching process is also named as a market clearing process. The detail algorithms of the clearing process will be introduced in Section V-A2.

D. Combinatorial Auction and Cooperative Auction

In some real world market activities, supplies and demands are more sophisticated. In some situations, buyers need to buy a basket or a structured combination of heterogeneous commodities:

- *Combinatorial Auction*: Buyers in the aforementioned VCG auction request a set of multiple auction commodities. The requested commodities may only be partly allocated, or fully allocated to the buyers. Each buyer will be satisfied if only some of the requested commodities are received. However, in some cases, the buyer needs a complete set of the commodities. Otherwise, the buyer will not be satisfied even if only a single requested commodity in the requested set is not received. To deal with such bidding requests, combinatorial auctions [13], [14] can be applied. Each bid submitted by the buyer expresses the need of a whole bundle of auction commodities. After collecting bids (and asks), the optimal commodity allocation is computed under the constraints indicated in the bids according to the buyers' requests. That is, each bid for the whole bundle is either fully accepted or rejected in a combinatorial auction.
- *Cooperative Auction*: A cooperative auction (or a group auction) [15] is relatively new as the emerging of Internet-based auctions. It benefits both buyers and sell-

ers, where sellers offer buyers price discounts according to the number of requested commodities (i.e., the more the requested, the lower the price). Buyers cooperatively group together to make a group bid and attempt to obtain commodities at low prices while sellers are willing to sell more quantities at the low prices. However, an article [16] points out that the price decreasing is actually sellers' market schemes, rather than the result of buyers' cooperation. In this survey, we mostly discuss systems with limited number of buyers, and sellers are tending to use simple market scheme, i.e., earn optimal revenue with certain constraints.

E. Other Auctions

- *Offline/Online auction*: An offline auction is an auction where buyers are allowed to make bids at any time, but the auction market is only cleared at certain specified time points. For example, the auctioneer waits and receives asks and bids for a pre-defined period. Then after the period, the market is cleared. The wait-and-clear process is defined as an auction period. However, in an online auction [17] and [18], whenever the asks and the bids arrive, the market is cleared immediately. The online auction is more complicated than the offline counterpart. However, it precisely fits to the practical wireless systems, where the auction requests could be generated randomly and need to be handled as soon as possible.
- *Anglo-Dutch Auction*: An Anglo-Dutch auction [19], [20] is a mixture of English and Dutch auctions. Buyers make ascending bids as in an English auction. During the English auction step (the first step), some buyers are gradually dropped out as the bidding price increases. When there are only two buyers left, these two buyers will start a first-price sealed-bid auction, which is equivalent to a two-person Dutch auction [3] (the second step). The initial price of the second step is not lower than the price bid by the last buyer dropped out during the English auction step. Some countries [21] have employed this two-step auction mechanism in spectrum license auctions.
- *Waiting-line Auction*: A waiting-line auction [22] is similar to a scenario that many people queue overnight for Black Friday deals. There is no explicit process of submitting bids. Instead, the buyers join a queue, and the seller will hand auction commodities sequentially to the buyers in the queue at some unknown time. The buyers do not know the actual allocation time beforehand. Auction commodities are so limited that only those who are in the front positions of the queue can be allocated with (better) commodities. However, to stay in the front, a buyer has to wait for longer time, consuming opportunity costs of time when waiting. That is, there is a trade-off between time and chance to win. A buyer might waste more time to wait if the buyer wants more chances to win the auction commodity.

F. Methodologies and Objectives of Auction Mechanism Design

Auction is a sub-field of mechanism design, which is an economic approach to motivate all participants in a system to choose their own strategies so that certain design objectives can be achieved. In other words, an auction mechanism motivates sellers and buyers to make asks and bids based on their own individual rationalities, and then the auction design objectives will be naturally achieved as expected. This section presents some terminologies and general concepts defined in the auction mechanism design to understand its methodologies and objectives.

- *Mechanism, social choice and strategy*: A mechanism mainly consists of two parts. The first part is the strategy submission of all the participants (i.e., buyers and sellers in auctions). Each participant has a private preference defined as a type, which affects the participant's strategies. The second part is the outcome evaluation of the system. A function which maps all participants' types to the outcome of the mechanism is called a social choice function. Specifically, in an auction mechanism, each buyer (or seller) has preferences on the auction commodities to be requested (or sold). The strategies are bids (or asks) submitted, reflecting the buyer's (or seller's) preferences. The set of auction rules produces the optimal mechanism outcomes that satisfy all the sellers and buyers. When applying an auction to a system, it is feasible to adopt existing auctions such as English auction and VCG auction. Otherwise, new auction mechanisms should be proposed, focusing on how the strategies are formed, and how the auction rules are designed to allocate the auction commodities to satisfy all the auction participants.
- *Utility, social welfare and incentive design*: In an auction, a buyer who receives a commodity has the utility equal to the difference between the valuation and the hammer price, while a seller who sells the commodity has the utility of the gap between the hammer price and the seller's valuation. Other auction participants' utilities are zero. The sum of all auction participants' utilities is defined as *social welfare*, indicating how much profit the mechanism produces to the market. A utility that is higher than zero indicates the gained profit, which is one kind of incentives to motivate more participants to join the auction. The auction mechanism should be designed to give the auction participants the incentives to attract bidding for the auction. Failing to do so, the auction market may collapse that too few participants are interested in the auction, and commodities are not efficiently allocated [23].
- *Equilibrium*: Game theory is a typical mathematical tool used to analyze the behaviors of buyers and sellers in an auction. The buyers and sellers will rationally make their own bids and asks (i.e., strategies) based on their knowledge of the mechanism and other auction participants. The objective of game theory is to analyze the equilibrium strategy of the buyers and sellers. The Nash equilibrium is the most common solution concept in game theory which ensures that none of players can unilaterally change strategy given that other players keep their strategies fixed. When using game theory to analyze an auction, it is also important to check the existence

and uniqueness of the Nash equilibrium. There also exist different solution concepts such as mixed-strategy equilibrium, Bayesian equilibrium [24], and correlated equilibrium [25] according to the auction mechanism design.

III. PUTTING AUCTIONS TO WORK: DYNAMIC RADIO RESOURCE MANAGEMENT

A. Development of Radio Resource Management

Long before the application of economic approaches (including auction) for resource management in wireless systems, static resource management was mainly used. In a statically managed system, resources are assigned to the users in a static manner. For example, before the spectrum license auctions, some countries use the first-come-first-served way to distribute spectrum licenses (e.g., Australia before 1992). Also, in other resource allocation processes like routing in a wireless network, fixed resource allocation plans may be also employed. Such static radio resource management is inefficient since the demand and supply of the resources do not always match.

The lack of efficiency of static allocation schemes can be eliminated by market-enabled pricing schemes. In such schemes, radio resources are labeled with different prices for the resource users to purchase. The prices reflect the demand of the users and can be decided either by the resource sellers or through the market competitions. The efficiency can be achieved by the market competitions. Various ways (including auction) to price the resources in a wireless network are discussed and compared in [26].

Auction is one of the pricing schemes which is widely applied to real world spectrum license allocation. Some certain bands of spectrum (i.e., the frequency for radio communications) are managed as restricted public resources by spectrum regulator authorities such as government agencies. Auction approaches are adopted by these authorities to sell the spectrum licenses which permit the license holders to access or redistribute specific bands of spectrum. Some famous spectrum authorities include Federal Communications Commission (FCC, US) and Radiocommunications Agency (UK). These spectrum licenses are auctioned as physical commodities. Generally, the spectrum license auction is not in a real-time manner. The authority takes a period to prepare and receive the bids from telecommunication companies and other institutions (i.e., buyers). Then the authority decides the winning buyers who can legally use the licenses until the contracts terminate or the authorities reclaim the licenses back due to economic or public interest. The time scale of this spectrum license auction is usually large, e.g., the government may only reclaim the licenses and hold another auction selling similar bands of spectrum every long period, which makes the auction formal and long-term [23]. Take the FCC auction No. 93 for bands of 88MHz-108MHz as an example, there are 109 qualified bidders making 37 rounds of bidding during about 9 days of auction period. 93 out of the total 119 licenses are successfully allocated. The mechanisms of auctions applied to such spectrum license allocation can vary from traditional English or Vickrey auction to specifically designed auctions. One of the most important objectives of the spectrum license auctions is incentive design. As the potential buyers consist of both small and large companies, the authorities have to design the auction mechanisms to encourage small companies to join and compete with large competitors [23].

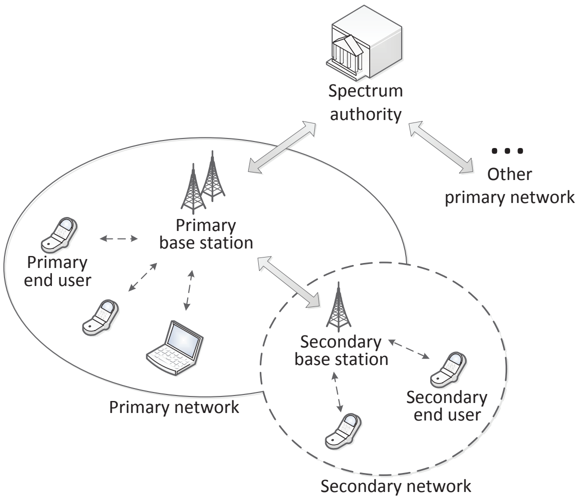


Fig. 2. The architecture of a typical cognitive radio system.

B. Cognitive Radio

A cognitive radio system is a typical and widely researched scenario where auctions can be applied. Cognitive radio can be used in both single-hop and multi-hop wireless networks. In traditional wireless communication systems, the right to use spectrum is fixed and managed by the spectrum owners. The long-term or fixed allocation scheme leads to inefficiency in spectrum usage [27], such as unused spectrum holes. Cognitive radio [27], [28] is an emerging wireless communication technique. Users in a cognitive radio system can opportunistically access the radio resources. In the theoretical studies and industry applications of cognitive radio systems, one possible single-hop hierarchical structure [10], [27], [29], [30] can be applied, as shown in Fig. 2.

According to Fig. 2, a cognitive radio system has three main components: *spectrum authorities*, *primary networks* and *secondary networks*. A spectrum authority is often the government organization who ultimately owns, manages and issues the spectrum rights. A primary network owns the licenses directly from the spectrum authorities to use the radio resources (e.g., telecom companies), while a secondary user has to dynamically request the available spectrum from the primary networks. In such the layered structure of cognitive radio systems, two types of auctions are considered [20]. Firstly, the auction taken between spectrum authorities and primary users (namely primary auction) are the conventional spectrum license auctions in Section III-A. Secondly, the auction between primary users and secondary users (i.e., secondary auction) is much more dynamic, which is reviewed in Section III-C and III-D. The primary users lease their available radio resources (i.e., spectrum), and the secondary users dynamically compete for the radio resources of the primary users. Such a secondary auction is held while the system is running. Auction participants need to make bids and asks dynamically. [31] generally discusses features and challenges of auction approaches in such cognitive radio markets.

There are three types of dynamic cognitive spectrum access models. Each model is linked to one type of auctions in wireless systems.

- *Exclusive-use*: Spectrum resources are assigned to the corresponding network users for a certain period of time. A user has exclusive access to the spectrum during that period, and releases the spectrum afterwards. The time scale of that period can be long in a *long-term exclusive-use* model, and can be more fine grained in a *dynamic exclusive-use* model. Spectrum license auctions between authorities and telecom firms are instances of long-term exclusive model. However, under the regulations of authorities, telecom firms can also transfer their spectrum rights to other firms, which is an example of dynamic exclusive-use model.
- *Shared-use of primary licensed spectrum*: The licensed spectrum already allocated to primary users is shared by other non-licensed secondary users dynamically. This is the secondary auction scenario. According to the level of interference caused by non-licensed users to licensed users, such a model can be categorized into *spectrum overlay* and *spectrum underlay* types. In spectrum overlay, the secondary users transmit on the different time and different channel from that of the primary user to avoid interference. In spectrum underlay, the secondary users transmit on the same channel as that of the primary user, but using low transmit power.
- *Commons*: In a model of "commons", spectrum is treated as a public resource and can be equally accessible to every user without central regulators. The spectrum is freely and fairly accessed, traded and controlled by the mass spectrum users. There should be no privileged component in the system. Such model is an ideal and completely free market model, which is less discussed in auction applications in wireless systems.

C. Auctions in Wireless Systems: Commoditization of Radio Resources

Conventional applications of auctions are mentioned in Section III-A. However, auctions are recently applied to radio resource management with distinguishing features. The auction process in a wireless system follows the mechanism design in Section II-F. Every buyer (or seller) has a private type on each auction commodity. The private type affects the buyer's (or seller's) valuation submitted to the auctioneer. The submitted valuation is named a bidding price (or asking price), which is not necessarily the true valuation on the commodity. The buyer (or seller) may purposely submit a false valuation to cheat for more received commodities with less payment. The auctioneer is the executor of mechanism who receives asks and bids, and generates auction results. Different auction mechanisms are deployed on the auctioneer to achieve design objectives, e.g., to maximize the sellers' total utility or to ensure the valuations submitted by buyers are truthful (i.e., true valuation).

To apply auction models to wireless systems, the dynamic allocated radio resources are defined as some types of auction commodities (or namely auction resources), as follows.

- *Subchannel*: In wireless network, the frequencies can be divided into subchannels (i.e., frequency division multiple access [FDMA] and orthogonal frequency-division multiple access [OFDMA]). Auctions can be used to allocate these available subchannels to the users (Fig. 3a). Subchannels are defined as *substitutable*, if all the subchannels are homogeneous and have the same quality to carry the data for transmission. Otherwise, the subchannels are *unsubstitutable*, if they are heterogeneous and in different qualities as for different buyers. e.g., frequency selective fading channels.
- *Time slot*: Spectrum resources can also be divided in a time domain (i.e., time division multiple access [TDMA]). An available time period for data transmission can be divided into time slots as auction commodities. Buyers and sellers have different valuations on different time slots according to time-varying channel qualities and users' preferences on whether to transmit immediately or in the future time slots.
- *Power or SINR level*: Multiple users can transmit data simultaneously on the same channel using different codes (i.e., code division multiple access [CDMA]). In such a network, the transmit power is an important parameter to determine the signal-to-interference-plus-noise ratio (SINR) and also the transmission by one user may cause interference to other users. The auctioneer can set the transmit power level or the interference limitation for users. The users as buyers have to pay higher price for higher transmit power, thus higher interference.
- *Transmission path*: Transmission paths can be allocated as auction commodities, as shown in Fig. 4b. Consider an auction in a mobile ad hoc network (MANET), data should be transmitted from the source node to the destination node. Generally, there are multiple available paths with different qualities (e.g., cost and distance) to be chosen. Paths with lower cost or shorter path are much more favored by source nodes (as buyers).
- *Network service*: A network service is a service provided for network users. As shown in Fig. 3b, each network service covers a particular area of the networks, and the network users in such area can choose to access different network services, e.g., WCDMA, Blue-tooth and IEEE 802.11. Such a system is referred to as the joint radio resource management (JRRM). The network services are defined as auction commodities, providing a certain quality of service (QoS) at a certain price [32].

D. Auctions in Wireless Systems: Implementations

In most existing works that propose auction approaches for the wireless networks, two types of wireless networks, i.e., single-hop and multi-hop wireless networks, are mainly involved.

Single-hop network is a typical architecture of wireless system. In a single-hop network, the communication among nodes can be direct (e.g., fully connected network) or between

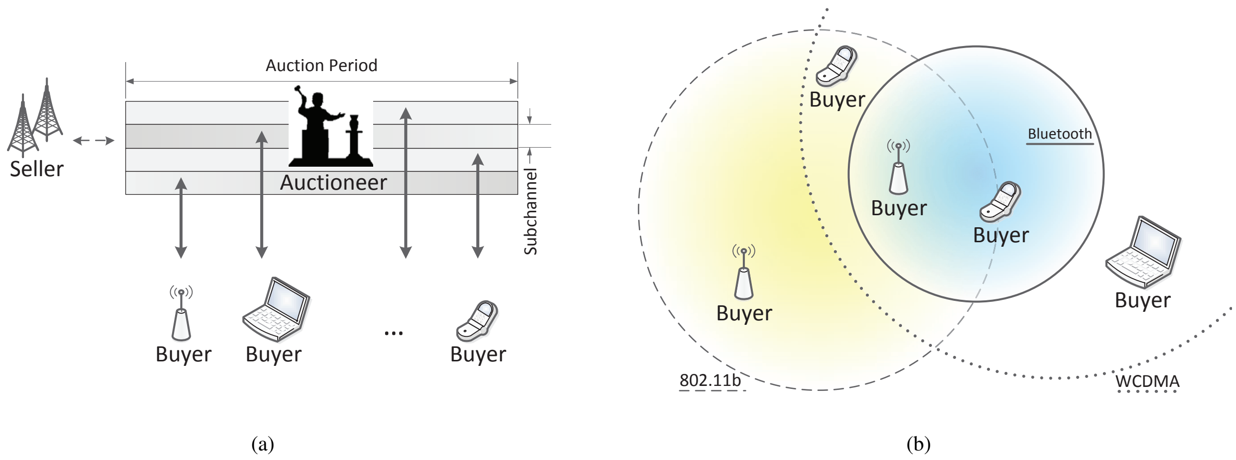


Fig. 3. (a) A spectrum auction for subchannels, (b) an auction for network services covering different area (e.g., the buyer in the middle is covered by Blue-tooth, 802.11b and WCDMA simultaneously).

nodes and base station (i.e., client-server fashion). The auction is applied in the single-hop network to allocate the radio resources for the communication. In the case of communication between the nodes and base station, the base station can be the auctioneer (on behalf of the seller). For example, in Fig. 4a, each secondary user is a buyer while the secondary base station acts as the role of the radio resource seller. The connection between each seller and buyer pair is only one hop.

Auctions are also frequently used in multi-hop wireless networks, e.g., a mobile ad-hoc network. In multi-hop wireless networks, the nodes are distributed as the network users. For every data message being transmitted in the network, the node that generates the data is defined as the source, and the node that will finally receive the data is defined as the destination (or sink), while other intermediate nodes are called (possible) relay nodes. The data can be routed along different intermediate nodes from the sources to the destinations (i.e., transmission paths). Therefore, the major difference between the auction used in single-hop and multi-hop networks is at the consideration of routing. To meet the performance requirements (e.g., throughput, latency, and power consumption), the source node tends to choose the optimal path, e.g., the shortest path, the path with fewest hops, or the path with the least power consumption. However, different nodes along paths usually belong to different owners who are rational and selfish [33], so there should be mechanisms to "encourage" nodes to collaborate to forward data. For this reason, auctions are designed in some literature as an incentive for nodes to cooperate.

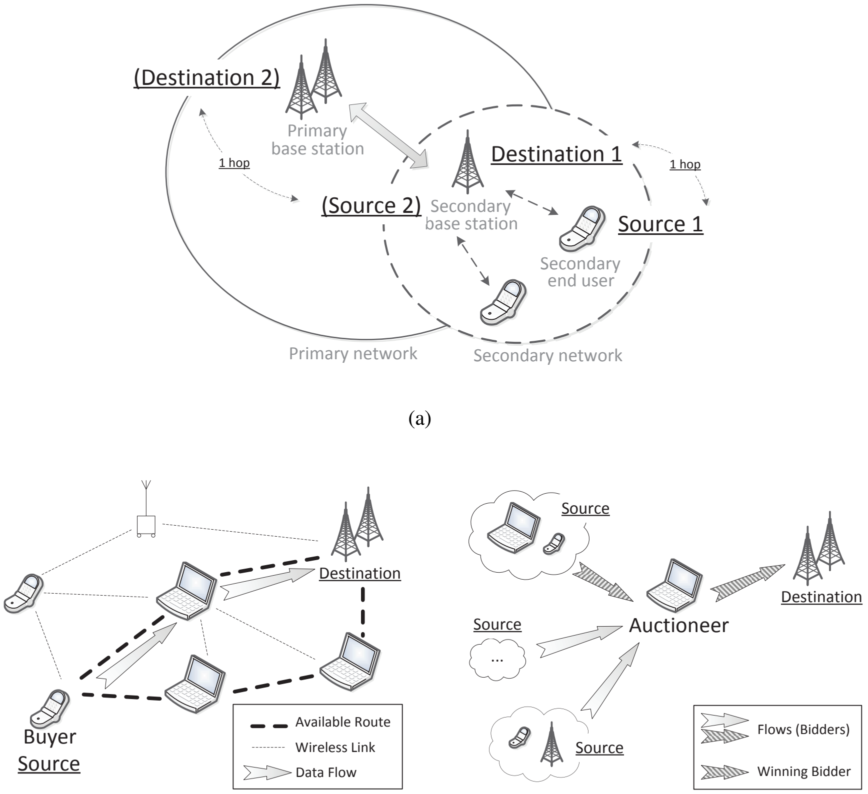
There are two types of auctions in multi-hop wireless networks. One intuitive type includes the auction for optimal paths (namely, path auctions) [34], [35], as shown in Fig. 4b. The buyers in such auctions are the source nodes of the data messages. The auction resources are defined to be the optimal paths from the source buyer nodes to the destination of the messages. The auctioneer may be a centralized entity to collect bids and allocate optimal paths to corresponding winning buyers. Usually, the payments made by the buyers are shared among the intermediate nodes along the optimal paths to stimulate them to be cooperative. Another type is the auction for subchannels or time slots in multi-hop wireless networks. Multiple data flows can reach an intermediate relay node at the same time. These flows (namely routes in some literature) can be considered as buyers, who compete for the access right to pass through that node [33], [36], [37], as shown in Fig. 4c. The type of the auction with data flows as buyers often falls into the scope of aforementioned single-hop auctions for subchannel/time slot of the intermediate node.

It should be noted that, when auction models are applied to wireless systems, there are also some design constraints and assumptions.

Firstly, extra communication overhead caused by auctions should be considered. In a conventional real life auction, the communication overhead of making asks/bids is always neglected. That is, no matter how complex the bidding/asking language structure (see Section IV-B) is, the bid/ask message can always reach the auctioneer on time, and has no impact on the auction results. However, in a wireless scenario, a bid/ask message could be so complex that it will consume too many radio resources (e.g., time slots) to transmit. In this situation, the impacts of auction on the communication overhead should be taken into consideration. A few studies (e.g., [38], [39]) discuss about the designs of simplified bid/ask message structure (i.e., bidding/asking language, Section IV-B) to lower down such impacts.

Secondly, in existing studies of auctions in wireless systems, transmissions of bidding/asking messages are assumed to be without loss or failure. However, auctions in wireless systems may be affected by channel losses and data delivery failures. For example, a successful bid process may end up with a failed payment transaction process and a buyer in a MANET who has won the auction for transmission path might not be able to transmit over the path due to the location change and unsuccessful access to the next hop. The actual transmission quality of radio environment could affect the auction applied, which should be further considered in future models and designs.

Moreover, security of auctions in wireless systems could be an important concern. In real world auctions, security is usually guaranteed by auction houses or third-party entities.



(a)

(b) (c)

Fig. 4. Network architectures for auctions in single-hop and multi-hop wireless networks: (a) A cognitive radio model as a single-hop wireless network, (b) optimal path auction in a multi-hop wireless network, (c) subchannel/time slot auction in a multi-hop wireless network.

For example, in a sealed-bid auction for 3G/4G licenses, each bid is submitted confidentially via certain secure channels to the spectrum authority (i.e., auctioneer), and the payment is transacted under the supervision of banks or other financial institutions. However, a wireless system is relatively an open environment. It could be easy to intercept the transmission channels and capture other auction players' bidding/asking/payment information. Therefore, the security problems in radio resource auctions become critical. A few existing studies [40], [41] employ encryption to secure the bidding/asking and payment in wireless system auctions. Yet, in most other studies, security issues are implicitly assumed to be implemented in the underlying wireless transmission protocols.

IV. BASICS OF AUCTION DESIGNS FOR RADIO RESOURCE ALLOCATION

In this section, we present the basic technical details of designing auctions to solve resource allocation problems in wireless networks.

A. *Currency Design, Payment and Account Settlement*

Currency, or generally referred to as money, is used as a medium for profit transferring among auction players, and an incentive for players to participate the auction. In a radio resource auction, the sellers sell resources to the buyers. Once the resources are allocated to the buyers, payments must be made from the buyers to the sellers by means of currency.

The payment processes are managed in a centralized or a distributed manner. In a centralized management model, auction participants have their accounts located in a "central bank entity" [42] of the system. All credit/debit transactions of currency are executed by the central bank entity in a centralized manner. The central bank entity could be the base station, or a specified controller. On the other hand, in a distributed management model, transactions and settlements are managed by the sellers and the buyers themselves. Since auction participants do not have to communicate with the centralized entity for their transactions, the communication overhead in common communication channels may be reduced.

The form of currency can be various in radio resource auctions, e.g., real cash (e.g., in governments' spectrum license auctions [21]), fictitious currency (i.e. token) and commodity.

1) Cash or Fictitious Token as Currency: In primary spectrum auctions conducted by government authorities, spectrum licenses are sold to telecom companies (i.e., buyers) for the future usage. In this case, the real cash is used as payment currencies [21], [20]. However, the payment by real cash is usually a physical process and may cause overhead to the system. There are some situations in which the fast transactions are needed. For example, in secondary spectrum auctions, radio resources should be dynamically allocated from the primary users to the secondary users in a short period of time. Another example scenario is a wireless sensor network, where the capacity of each node (i.e. a radio resource buyer) is limited and it is unrealistic to make real cash payments. Therefore, fictitious currency is employed as in [34] and [43], which is designed to be a simple digital signal with a certain value, representing an equivalent of a certain amount of real cash. Fictitious currency has the advantage that it is easy to be circulated in the wireless environment due to the simple structure. Yet, this fictitious currency design has drawbacks that there are chances that such currency is counterfeited by other auction participants.

The connection between cash and fictitious currency is intuitive. Fictitious currency is treated as a type of paperless cash and can be exchanged with real cash via some agencies [33], [35]. Based on this fact, [33] mentions that specialized commercial nodes to earn profits in a multi-hop wireless network may emerge in the future radio resource auction designs.

2) Commodities as Currency: In some radio resource auctions, sellers and buyers can also use commodities as a form of trading currency under a barter-like trading rule. In such auctions, sellers and buyers offer their redundant resources to trade for other resources in demand.

Time slots are paid in the form of currency as shown in [44], [45] and [46]. Since the time slot resource is non-storable, the buyers in an auction will trade the future rights of using time slots for the immediate time slots. That is, the buyer who wins an immediate access to current time slots will surrender the right to use future time slots as payment to the other auction participants who prefer to wait and use those time slots in the future. For example, [44] and [45] discuss a cognitive radio system where time slots are treated as auction resources, as follows. The whole transmission period is divided into frames, and each frame is divided into time slots to be auctioned. The last time slot within a frame is defined as an out-band sensing time slot, and the rest are time slots for transmission. As the radio environment can change over time, the secondary users (i.e., the buyers) have to use the out-band sensing time slot to sense and decide whether to dynamically switch to the other available subchannels in the next time frame. In the proposed auction mechanism, the buyers who have successfully obtained time slots within a time frame have to forfeit their out-band sensing time proportional to the obtained transmission times slots.

Transmit power is also used as a form of currency in some auction mechanism designs. For example, in [46] and [47], the primary users have redundant or reserved radio resources (e.g., time slots) to sell to the secondary users, while the secondary users pay out available redundant power as currency to buy the radio resources from the primary users. Then the primary users will utilize the secondary users' reserved power to relay data. Simulation results show that by trading secondary users' power for primary users' resources (available bandwidth), the secondary users' total transmission rate increases, while the primary users' average consumed power is reduced. The mechanisms in [46] and [47] have a drawback that if there are not enough buyers making bids and paying out their time slots, the base station (seller) may not have enough chance to successfully relay data, and the relay transmission may fail.

B. Bidding Language Design

Bidding languages are expressions of information exchanged among sellers and buyers in radio resource auctions. The bidding languages used in the same auction must be commonly known to all the auction participants. Otherwise, the sellers and buyers are not able to communicate to complete the auction process. A bidding language can be in various forms. For example, raising a bidding paddle in an antique auction is a kind of traditional bidding languages. In radio resource auctions, bidding languages are packet messages including bidding information (e.g., requests of radio resources and the valuation), which are sent from buyers to the sellers selling the radio resources.

Two of the most critical considerations of designing a bidding language are expressiveness and efficiency of the language. The bidding language can be designed either simple or complex to achieve expressiveness or efficiency. A simple bidding language contains only a small amount of information in a plain structure, and causes small overhead to the communication channels, i.e., a simple language is efficient for transmission. However, such simple languages may not carry enough information to express some complex auction requests (e.g., bids in a combinatorial auction). Complex bidding languages are developed to express such compound auction requests. A complex bidding language may contain a rich amount of bidding information as well as a well-organized structure. The information and structure contained enhance the expressiveness of the language, but cause more overhead to the wireless channels and hence reduce the efficiency. Therefore, bidding languages should be well designed in radio resource auctions, taking trade-offs of expressiveness and efficiency into consideration [48].

In different auction mechanism designs, the buyers may have different patterns to submit their bidding languages. During each auction period, each buyer can only submit one bid message (defined as *one-shot bid*) or several bids repeatedly (defined as *multi-shot bid*). Furthermore, in each message that the buyer submitted to the seller, there can be only one single bidding request (i.e., single-bid), or multiple structured bidding requests (i.e., multi-bid) included. For example, a single-bid bidding language may contain a bidding pair $(\mathcal{F}_{b_i}, p_i)$ indicating that the buyer b_i requests a range of frequency $\mathcal{F}_{b_i}$ at the price p_i. [17] and [18] also introduce a single-bid language, where each bid is a tuple set (four-tuple in [17] and six-tuple in [18]) containing the buyer's name, valuation on the resource (time slot), and requested time slots. A single-bid bidding language has a simple structure to guarantee its efficiency in the communication (i.e., a simple bidding language). However, a multi-bid bidding language includes several single-bids (or namely atomic bids), expressing more complex bidding requests.

For example, the "OR bid" [48] of M atomic bids can be used to express the radio resource buyer's request for any frequency f_i at the price p_i, $i = 1, 2, \ldots, M$, i.e.,

$$(f_1, p_1) \; OR \; (f_2, p_2) \; OR \; \cdots \; OR \; (f_M, p_M).$$

Moreover, [49] employs a one-shot multi-bid auction. Each resource buyer submits a one-shot bid which is a set of $price-amount$ pairs to the resource sellers.

In addition to the single-bid and multi-bid bidding languages, [38] proposes bidding languages to improve the speed of the transmission and calculation processes. Each buyer just submits a piecewise linear price-demand (PLPD) function as its biding strategy, instead of a set including multiple atomic bids. Coefficients of the linear functions reflect users' bidding preferences, or namely, bidding behaviours. PLPD functions have simple linear (also continuous and concave) forms and can approximate users' bidding strategies, so the optimization problem such as a revenue-maximization can be easily solved. [39] allows users to have different bidding strategy functions. Users even do not really submit bids for every slot because that may cause a lot of communication overhead. Instead, network operators (i.e., base station) provide some bidding functions for users to choose. A user just needs to choose one from those bidding functions according to the bidding preferences of the user.

C. Bidding Strategy Adaption

Game theory is the most common tool to analyze the behavior of rational entities in an auction. In the auction, users can adapt their bidding strategies dynamically to be competitive and to achieve the highest utility. The strategy adaptation could be from the change of environment (e.g., time-varying channel quality) and the change of other users' strategies (e.g., by learning and gaining knowledge from past auction results). To adapt the strategy optimally, learning algorithms can be used to improve the performance of an auction over time, and to reach the equilibrium solution.

Several works focus on the strategy adaption and updating techniques. These techniques are mostly based on past auction results and other auction participants' empirical or statistical information. For example, a strategy updating algorithm in [50] is based on a history of bidding and allocation results, as well as auction participants' current statuses and estimated future auction results. The future auction results can be estimated by the proposed best-response learning algorithm without fully knowing other buyers information. By using reinforcement learning (Q-learning) techniques [51], both buyers and sellers in [52] learn from the past auction results to decide the future bidding and asking prices, and thus maximize the total revenue. [47] presents strategy updating schemes for both centralized and distributed auctions in cognitive radio systems. In the centralized approach, an intuitive reinforcement learning algorithm is employed by the radio resource buyers (i.e., secondary spectrum users) to adjust their bidding strategies. The knowledge that these buyers learn from is *ex post* information receiving from the centralized source (e.g., a centralized auction controller or a base station). In the distributed approach, each of the sellers (i.e., primary spectrum users) does not reveal auction knowledge to the buyers. However, based on the past auction results, the seller can still update step by step the amount and quality of the available spectrum resources which are to be priced and allocated to the buyers. Similar to the centralized approach in [47] and [50], the past auction results are revealed by the auctioneer (representing the seller) in [53]. A Bayesian nonparametric scheme based on the Dirichlet process is employed by the radio resource buyers (i.e., secondary users) to update knowledge. Also, a suboptimal algorithm with linear complexity to the number of auction commodities (i.e., subchannels) is developed for the buyers to estimate their future auction utilities. By this approach, the buyers can alter bidding strategies during the auction based on estimated utilities. By analyses and simulations, the strategy updating scheme [53] leads to better achieved utilities of the radio resource buyers, comparing to a myopic bidding scheme where the bidding strategies are optimized based on the current condition only.

D. Fairness and Efficiency Designs

The efficiency objective [54], [55] in auctions is generally allocative efficiency, also known as Pareto efficiency, i.e., each auction commodity is allocated to the buyer who has the highest valuation on that commodity. By realizing efficiency, the auctioneer can maximize the total payment from the buyers, and thus obtains the maximized revenue. On the other hand, fairness ensures that different participants can benefit fairly and be treated equally in the auction. There are different levels of fairness which can be designed to fulfill different requirements of the auction mechanisms. For example, basic fairness [56] only ensures that different buyers (or sellers) have the same chance to participate an auction, while the max-min fairness [43] ensures that all buyers (or sellers) at least receive a basic amount of auction commodities. According to the definitions, efficiency and fairness measurements are not achievable at the same time. For example, if only efficiency is guaranteed, the fairness would be to some extent affected since the buyers with low valuations would not receive the commodities. There should be trade-offs between these two metrics in auctions for wireless networks.

Efficiency in auctions for radio resource allocation is focused in [53]. In each auction period, the proposed mechanism requires the buyers to contribute an "entrance fee" to the seller (the primary user) once the buyers want to participate the current auction period. As we mentioned, the resource buyers (i.e., secondary users) can build the knowledge by learning from the past auction results, and autonomously decide whether to participate the auction or not. By this mean, the entrance fee works as a threshold to reject the buyers with too low valuations on radio resources to enter the auction. In this auction mechanism, efficiency objective is achieved by the "invisible hand theory" in economics, i.e., ideally, competitions of self-interested and price-taking auction participants will naturally reach an equilibrium, and form an efficient auction market.

Fairness in auctions for spectrum resources is discussed in [53] and [57]. [53] guarantees basic fairness of the mechanism in the long run of the auction process. As mentioned, the buyers with relatively higher valuations are more likely to participate the auction. However, as the auction proceeds, buyers with high valuations will gradually drop out because of the entrance fee cost, and other low budget buyers will have chance to compete and win a part of resources in the later period of the auction. Thus, fairness is guaranteed to some extent. Moreover, fairness is also studied in [57], where the fairness index inspired from [58] is proposed, as follows:

$$F(u, N) = \frac{(\sum_{i=1}^{N} u_i)^2}{N \cdot (\sum_{i=1}^{N} u_i^2)}. \quad (1)$$

The fairness index is a function of the total number of the resource buyers N and utilities u_i of buyer i. The value of the fairness index indicates the degree of fairness of an auction mechanism. The mechanism with the large value indicates that the mechanism evenly allocates auction resources to the buyers while the mechanism with the small value is relatively unfair, so the resource buyers with higher valuations will be favored. Such a fairness concept has two usages. Firstly, the mechanism auctioneer who controls the auction and allocation can either maximize or minimize the fairness index to achieve fairness or efficiency objective, respectively. For example, the fairness is controlled and managed by the seller side (i.e., the primary user) in [57]. The maximization of fairness index is included as one of the objectives in the optimization problem formulated for the auction. Secondly, the fairness index can be employed as an *ex post* metric to quantitatively measure the fairness of the system. For example, assuming that there are several auction designs, it is possible to tell which auction is more fair by simply calculating the fairness index after the allocations are completed.

E. Incentive Compatibility

Incentive compatibility or truthfulness, is an important aspect of auction designs. Generally, the buyers send bids to the sellers during the auction process. However, to gain more profit by any means, the buyers may send false information about the buyers' private information. For example, in an auction for packet routing in a mobile ad hoc network, data transmission has two steps, i.e., the route discovery and data transmission. Since nodes are generally assumed to be selfish, they tend to deceive other nodes about their own information, by which some of them may earn more profit but the social welfare is impaired. As defined, in radio resource auctions, incentive compatibility feature guarantees that the resource buyers will receive optimal utilities if the bids that they submitted truthfully reflect their real valuations on the requested resources. That is, for every rational auction participant, to submit the truthful bid is always the dominant strategy.

To achieve incentive compatibility, the auction mechanism should be designed to guarantee that the buyers' dominant bidding strategies are the truthful bidding strategies. That is, each buyer's social choice is to submit the true valuation no matter what other buyers' bidding strategies are. A simpler approach to achieve incentive compatibility is to directly apply the existing auction mechanisms that are proved to be incentive compatible (e.g., the typical VCG auction mechanism guarantees incentive compatibility [59]). If the setting and bidding process of a radio resource auction follow those of the VCG auction, resource buyers will prefer truthful biddings as their dominant strategies. [34] proposes an extended version of VCG auction for route allocation in mobile ad hoc networks, where messages need to be forwarded from the source to the destination. The scenario is a reversed VCG auction that several sellers compete to sell the transmit power to one buyer. Each node (as seller) submits a private cost-of-energy value to the message source (as buyer). The message source will discover and choose the best path with the optimal cost and offer some incentives (e.g., monetary payments) to the nodes along the path. Due to the truthfulness feature of the VCG auction, the nodes will truthfully report the cost of using their transmit power.

To guarantee the incentive compatibility (as well as other features), the setting and process of the radio resource auctions should be identical to the existing auction mechanisms. However, some wireless networks may not fully satisfy this requirement. According to [35] and [42], the valuation information of each resource buyer in the mobile ad hoc network may not be totally private. Each buyer can "hear" the valuation information from other buyers because of the medium sharing of the wireless environment. [35] then argues that the mechanism in [34] will fail to achieve incentive compatibility due to the lack of privacy. As an improvement, [35] presents a cryptographic technique to protect the privacy of information transmitted between buyers and sellers, thus eliminates leakage of private information.

F. Resource Reuse, Profit Sharing, and Collision Issues

Conventionally, auction commodities are not reusable. That is, if an auction commodity is claimed by one buyer, it cannot be allocated again to other buyers. However, in an auction for radio resource allocation, the commodity can be reused under certain conditions. For example, in a cognitive radio system, a frequency resource (i.e., auction commodity) can be used by several secondary users (i.e., buyers) at the same time for transmission, as long as the secondary users are in different cells and do not interfere with each other. As a result of such fundamental difference between conventional and radio resource auctions, several critical problems such as profit sharing and collision issues should be discussed.

In some auction, multiple buyers who bid for the same radio resource can win the auction (e.g., multiple users can gain access of the same channel for transmission using CDMA). The auction is thus a multi-winner auction [60], where the multiple buyers who bid for the same radio resource (subchannel) are put into a group. Each of the group is defined as a virtual bidder, containing individual buyers. By this mean, the multi-winner auction is transformed into a conventional auction with virtual bidders who act like normal buyers. The bid submitted by the virtual bidder is based on the valuations of all individual buyers composing the virtual bidder. As defined in [60] each virtual bidder's valuation on the auction commodity is the sum of all actual individual buyers contained in the virtual bidder group.

However, [60] neglects how the profit will be shared among individual buyers in the same virtual bidder group. [36] and [61] argue that as the entities (i.e., resource buyers and sellers) in a wireless network belong to different independent sources, these entities will not naturally cooperate. Profit sharing works as an ultimate incentive for them to cooperate to form a group (i.e., virtual bidder). Generally, profit earned by a group should be shared proportionally to the contribution of each group member. Analyses and shortcomings of some basic sharing methods are discussed in [62] and [63]. Two constraints are introduced for profit sharing algorithms in [62] and [63] to eliminate the shortcomings of basic sharing methods, as follows. Firstly, the member in a group should at least contribute some value to receive a part of the profit, i.e., there should not be any free-riders. Secondly, all the shared profit should be non-negative, i.e., group members do not have to pay extra fees to share the profit. Another profit sharing algorithm is proposed in [64], where a virtual bidder who has won the requested resource is considered as a coalition of multiple winners. Total utility (i.e., profit) obtained by the virtual bidder, as well as the payment amount are shared among buyers in that virtual bidder by using Shapley value [65] computed from each individual buyer's valuation. By this method, each individual buyer receives part of the total utility according to the marginal contribution provided by that buyer for the virtual bidder to successfully obtain the resource.

Resource reuse in wireless systems may still cause problems, such as collision. According to the definition of virtual bidder concept [60], two individual buyers in the same virtual bidder group must not physically interfere with each other. Therefore, the collision issues become constraints in optimization problems formulated for auctions for resources in wireless systems. Conflict graph model [38] is introduced to describe such constraints. Vertices in a conflict graph represent the buyers (i.e., spectrum users) in the system, and the edges represent interference relations, i.e., adjacent vertices connected by an edge interfere with each other. A coexistent matrix [66] and a conflict matrix [67] are also introduced to describe the conflict graph of buyers. [38] and [68] show that the collision constraints will make the optimization problems NP-complete. Also, [69] and [70] find that the interference-free allocation is essentially a classical graph-coloring problem. To reduce the complexity of solving the problem in the context of collision, [38] and [71] linearize the collision constraints into simple polynomial expressions. Although the problem is still NP-hard, approximate algorithms can be applied and sub-optimal solutions can be obtained. According to the simulations in [38], the sub-optimal results is computationally acceptable.

Another kind of collision in radio resource auctions is considered in [72]. In the proposed cognitive radio system, both traditional non-cognitive users and cognitive users exist together in the system. They share the same radio environment supported by a radio service provider (the resource seller). Cognitive users dynamically bid for spectrum resource from the seller, which may cause interference to non-cognitive users who statically stick to the licensed spectrum. In the designed mechanism in [72], if the collision is under a certain tolerable level, non-cognitive users are paid with some amount of compensations by the service provider, i.e., non-cognitive users share the service provider's revenue from cognitive users' participation. In this way, collision is converted into non-cognitive users' incentives to allow cognitive users to share primary spectrum resources. As a result, all the players in the auction can gain profits from the mechanism.

G. Collusion and Security Issues

Generally, it is assumed that the participants in a radio resource auctions only have local knowledge [73], [74]. That is, each of the buyers or sellers does not have complete knowledge of other participants and the whole system. Take the buyers for example, the bidding decisions (i.e., strategies) are made based on the buyer's own private information as well as limited public knowledge that other participants have revealed. Also, it is generally assumed that the participants in the auction are self-interested. Therefore, these radio resource buyers and sellers may form a group and collude with other auction participants by releasing false information. Such an action is referred to as collusion. [75] reviews the techniques to form and detect collusions in general situations.

According to [76], collusion will harass the performance of designed auctions. For example, in a spectrum license auction, there may be a large telecom firm together with several small telecom firms participating the auction. The big firm can bribe the small firms, letting them not make bids with high bidding prices. By colluding with other small firms, the large firm may win the auction at a very low final hammer price. The money used to bribe the small firms together with the money paid to the seller may be much lower than the large firm's true valuation on the license. During this process, the seller will receive lower revenue of selling the spectrum license because of collusion. In a wireless system using auction to allocate resources, the users (as resource buyers) work in a distributed manner and have chance to collude in similar ways. Although the buyers may belong to different authorities, collusion is still inevitable if the "illicit" profit is too attractive. Some known auction mechanisms are vulnerable to collusion. [5] also describes a situation where the buyers in the VCG auction may use collusion to lower the payments down to zero by using the second-price feature of the VCG auction.

As we mentioned, resource buyers and sellers in a radio resource auction only have limited knowledge. Therefore, it is critical for each auction participant to detect and avoid collusion, i.e., to apply collusion-resistant mechanisms. Generally, the collusion-resistant mechanisms are based on building collusion knowledge by analyzing past auction results and other publicly known information revealed by other participants (e.g., the bidding price called out by others). To prevent collusion, [77] proposes a belief function to describe the belief of the spectrum sellers (i.e., primary users) and buyers (i.e., secondary users) about each other side. The belief function of each resource buyer or seller is defined to be based on local information and parameters to estimate other auction participants' behaviours, i.e., global information. [78] extends [77] by applying the belief function into a multi-stage double auction of radio resources. Auction participants (especially the sellers) maintain their belief functions, and keep updating the function with the results of each auction period. To reduce the impact of collusions, each of the sellers has a reserved price computed from the belief function. Once the bid price drops lower than that reserved price, the primary spectrum seller will refuse to sell the resource. When collusion happens among some resource buyers, the bid price pattern will change and the social welfare will decrease. These changes may cause the belief functions of the spectrum sellers to change sharply, and hence break the reserved price threshold. On the other hand, the resource buyers can also employ the belief function approach to prevent collusions of the spectrum sellers.

In radio resource auctions, other kinds of security problems and fraudulent actions may also exist besides collusion. Previously, only the deceiving behavior of buyers are discussed. However, the seller (or the auctioneer) in the system may also deceive the resource buyers by overcharging. For example, according to [40], it is possible that the seller may arbitrarily charge the auction winner with a price higher than the price that the auction mechanism generated. [40] proposes an auction mechanism named THEMIS employing Paillier cryptosystem [79] to deal with the seller-side fraudulent actions. By using encryption, the actual value of bid submitted by each buyer is encrypted and unknown to both the seller and other buyers. The Paillier cryptosystem only allows the seller (i.e., the auctioneer) to compare the bids collected. Based on the comparison results, the seller decides the winner and the allocation schemes, while the buyer makes the payment according to the rules of the auction mechanism. For example, in a VCG auction with encryption proposed in [40] and [79], the truthfulness of buyers is guaranteed by the mechanism in the VCG auction itself, and the deception of the sellers is forbidden by the encryption technique. As a result, fraudulent actions of both parties can be eliminated. [41] proposes a secure combinatorial spectrum auction (SCSA), which extends [40] to support combinatorial auctions. Another encryption method named homomorphic encryption [80] is adopted to secure the communications. SCSA works in the similar way as THEMIS [40], but has lower computational complexity because that buyers in THEMIS [40] use broadcast as the communication pattern when making bids, while buyers in SCSA [41] only submit their bids to specific groups of sellers.

V. Auction-Based Approaches for Single-hop Networks

A general survey on auction approaches in single-hop wireless networks (e.g., the cognitive radio system model shown in Fig. 4a, and telecommunication system) is presented in this section.

A. Subchannel and Time Slots Auctions

1) Single-sided Auctions: In a single-sided auction, there are usually one seller and multiple buyers. The auctioneer who works as an auction conductor can be either an independent entity or integrated in the seller. The seller usually owns and sells a single or multiple radio resources (e.g., subchannels and time slots). Buyers, who are radio resource users, make different bids to buy those resources.

[81] proposes a single-sided auction mechanism named VERITAS for subchannels allocation. In VERITAS, the auctioneer can apply different allocation methods to achieve different objectives (e.g., highest fairness and maximum auctioneer's revenue), since the auction mechanisms inherently allow bid submission, resource allocation and payment processes to be independent. [29] discusses a single-sided sealed-bid auction. In [29], each secondary user (as a buyer) can lease only one subchannel during one auction period. Two scenarios are analyzed that the buyers can submit bids sequentially or concurrently during one auction period. Concurrent bidding pattern requires that all the buyers make their bids at the same time, and the losing buyers with conflicted bids (i.e., bidding for the same resources) will fail to obtain the requested resources. On the other hand, a sequential bidding requires that every radio resource is auctioned sequentially by the auctioneer, so that every resource will be allocated to a certain buyer. From the definition, the sequential bidding pattern provides better results than the concurrent one in terms of the resource allocation efficiency. This is because all the subchannels will be finally sold in a sequential bidding. However, concurrent bidding pattern has less communication overhead, since each buyer has only one chance to make a bid.

Auctions for a single resource may not be suitable for practical systems such as cognitive radio and OFDMA systems with multiple radio resources (i.e., subchannels) to be allocated. The auction for such systems with multiple auction commodities are modeled in [29], [30], [82], [83]. During an auction period, each buyer who submitted a bid can receive at most one single subchannel out of all the multiple available subchannels from the seller. [82] focuses on designing each user's valuation function which expresses the buyer's willingness to receive the requested subchannel. The function is defined as the gap between the user's transmission rate over the requested subchannel and the user's maximum transmission rate over any other subchannels. In [29] and [30], the allocation process by the auctioneer is modeled as a knapsack problem to maximize the auctioneer's revenue. The available subchannels are the sacks, while the spectrum buyers' requests for those subchannels are treated as items to fill the sacks. Unlike the mechanism in [82] that a user requests only one subchannel, each user in the OFDM system may request multiple radio resources during an auction period [83]. Each user submits several uncorrelated bids to avoid applying a combinatorial auction [13] which has high computational complexity. After collecting all bids, a greedy algorithm method is employed by the auctioneer to allocate subchannels. The payment is calculated according to the VCG mechanism.

A single-sided waiting-line auction [22] is applied to spectrum allocation in [84]. Instead of submitting bids in terms of money for resources, each buyer (i.e., secondary spectrum user) in the waiting-line auction informs a time to the spectrum seller (i.e., primary user). The submitted time indicates how long the user can wait until receiving the requested spectrum resource (i.e., the access right to the channel). It is assumed in [84] that each user has an opportunity cost which is positively related to time. That means, each user's utility will decrease as the waiting-time increases. Similar to rich and poor people situations in the real world, secondary spectrum users with higher budget are defined to have relatively higher opportunity costs over time, comparing to those of the users with lower budget. As a result, users with high budget eager to submit a short time value and receive the requested resources as fast as possible because of the high opportunity costs. On the other hand, the low budget users who have low opportunity cost can wait and receive resources later and thus pay less.

However, this is only the case when resource supply surpasses demand in the system. Otherwise, the high budget users may occupy all the transmission time as long as their utilities are positive, leaving no chance for the low budget users to transmit the data.

[43] and [85] analyze equilibria of single-sided spectrum auctions. An equilibrium in a radio resource auction is defined as the situation that no seller and buyer would change their auction strategies [12]. [43] focuses on the auctions for time slots. The Nash equilibria are found in the case of general communication channel state distribution. [43] also argues that the Nash equilibrium is usually not unique except when the channel distribution is uniform over [0,1]. It is then proved that each Nash equilibrium strategy leads to a Pareto optimal allocation scheme. [85] discusses the case of two users (i.e., buyers) and multiple available auction resources (i.e., channel or power) from the seller side. The sequential second-price auction [29] is proved to have a unique equilibrium of allocation scheme. For the situation of more than two users who have concave utility functions, there exists at least one pure strategy equilibrium in the auction.

2) Double-sided Auctions: As defined, double-sided auctions (also known as double auctions) are modeled for the scenarios of multiple radio resource sellers and buyers in the system. Double auctions in cognitive radio systems are proposed in [9], [10]. Both the primary users (i.e., sellers) and secondary users (i.e., buyers) submit their asks and bids respectively for the subchannels or time slots. There can be a centralized entity working as the auctioneer to match the asks and bids (i.e., supply and demand). In this process, buyers obtain resources while the sellers receive payments all based on the (optimal) matching rules. The matching process is also named as a market clearing process.

Simply extending the single-sided auction to its double-sided version may bring some side-effects [9]. Take the single-sided VERITAS [81] auction as an example, the simple extension of VERITAS is merely combining the sellers together, without any specially designed mechanism for the seller side. There is a chance for the seller to make untruthful bids [9]. Mechanisms should be specifically tailored for double-sided market scenarios. For example, [10] proposes a double auction mechanism for joint spectrum bidding and wireless service pricing in IEEE 802.22 WRAN systems. The double auction aims at maximizing the wireless spectrum providers' (i.e., spectrum buyers') revenue. The auction is then analyzed and solved as a non-cooperative game.

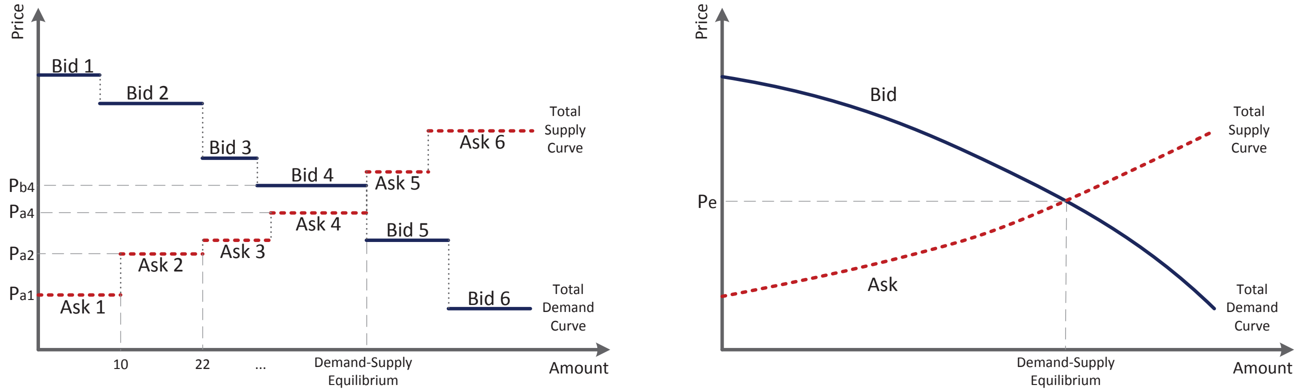
The core problem of double auctions is the algorithm of the clearing process. A general clearing algorithm for double auctions is stated as follows. The auctioneer collects all the asks and bids from the radio resource sellers and buyers, respectively. After then, the asks and bids are sorted according to the their indicated prices. These asks and bids form the curves of supply (i.e., asks from sellers) and demand (i.e., bids from buyers), as shown in Fig. 5a. The x-axis of Fig. 5a is the amount of resources to be sold/bought, and y-axis denotes the ask/bid prices. For example, on the supply curve, one radio resource seller asks to sell 10 shares of resources (e.g., subchannels) at the price P_{a1} (i.e., Ask 1), and another seller sells 12 shares of resources at the price P_{a2} (i.e., Ask 2), so on and so forth. Fig. 5a which is formed by asks and bids is a discretized version of the supply and demand curves (e.g., Fig. 5b) from economics. The intersection point of the supply and demand curves is defined as the supply-demand equilibrium [3], or namely competitive equilibrium. Usually in the double auction with discrete supply and demand, there are more than one intersection point as competitive equilibria, e.g., the price between P_{a4} and P_{b4} in Fig. 5a. The equilibrium is often used as the uniform clearing price of the double auction. The buyers and sellers deal at that uniform clearing price. If multiple possible clearing prices exist, any price in those multiple prices can be adopted by the auctioneer as the uniform clearing price. The auctioneer may also set different clearing price for every pair of matched buyer and seller. However, that significantly increases the complexity of auction rules and clearing process.

Similar to [81], the clearing (including pricing and allocation) algorithms of the auctioneer can be independent of other processes. As a result, different allocation schemes can be applied based on pre-determined performance objectives of the auction design. To show the independent allocation feature, four different allocation algorithms are simulated and compared numerically in terms of allocation efficiency. The computational complexity problem of a market clearing process exists in many double auction designs. For example, [71] argues that the market clearing algorithm in the proposed first-price sealed bid double auction is NP-hard. A heuristic algorithm is then employed as a sub-optimal polynomial time market clearing algorithm, which sheds light on the solution of such kind of problems.

In the aforementioned works [9], [10], auction commodities (i.e., subchannels) are sold by the primary users to the secondary users. However, [86] and [87] provide a novel idea that the primary user may just work as an intermediate broker of the spectrum market (or a market maker [88]). A secondary user (namely, cognitive user in [86] and operator in [87]) can act both roles of spectrum seller and buyer. Actually the proposed double auction [86] is an analogue of stock market, where heterogeneous subchannels with different qualities are traded among all the cognitive users (including primary and secondary users). [52] also adopts the similar design that each network provider who owns spectrum resources can either be a seller or a buyer. Due to the competitiveness of the market, utilization of resources are gradually optimized during the auction. Also, each user's utility is proved to be asymptotically maximized [86].

3) Online Auctions: Conventionally, auctions are held in an offline manner, i.e., the auctioneer collects bids and clears the market only at a certain time. However, the offline auction may not be suitable for dynamic radio resource allocation. For example, a spectrum user (i.e., buyer) needs the resource urgently before the auctioneer clears the market. Online auctions are more practical for such scenarios. Radio resource buyers can submit bids for resources at any time, while the auctioneer (or resource sellers) can allocate the requested resources immediately to satisfy the buyers' needs.

A synchronous auction mechanism for spectrum allocation is proposed in [29], [30], which is essentially a single-sided offline auction. The synchronous auction requires spectrum



(a) (b)

Fig. 5. (a) Discrete supply and demand curves of a double auction, and (b) continuous supply and demand curves of a double auction.

buyers to make bids simultaneously. In the synchronous auction, the spectrum resources will only be allocated/de-allocated at the fixed time intervals. The online counterpart of the offline synchronous auction is also proposed in [29] and [30], named asynchronous auction. At any time of the auction, the bids can be submitted and the resources can be allocated/de-allocated. It is proved in [29] that the offline auction outperforms the online auction (in a multiple resource auction scenario), since the bids arrive at the auctioneer stochastically in an online auction that the auctioneer has to take efforts to handle the randomness in such an online situation.

Double-sided online auctions are focused in [17], [18]. Primary spectrum users (i.e., sellers) and secondary spectrum users (i.e., buyers) send their asks and bids respectively to a centralized auctioneer to match the supply and demand of radio resources. According to the system setting, a single channel is shared as a public resource in the cognitive radio system. The channel is divided into time slots, each of which is defined as an auction commodity. [17] proposes an auction mechanism named truthful online double auction (TODA). TODA is employed in a (quasi-)double auction scenario, where the sellers submit their asks only before the auction starts, and bids from the buyers arrive following Poisson distribution during the auction. The bidding prices from the buyers also follow some certain distributions, which are assumed to be known by the auctioneer. The simulation results indicate the performance (in terms of the buyers' total utility) of TODA is not less than 80% of the performance of an offline VCG mechanism applied to the system in [17]. Another double online auction named strategyproof online spectrum admission (SALSA) is presented in [18] to deal with more general cases than that in [17]. In the two cases analyzed in [18], the bids from buyers still follow Poisson distribution, but Poisson arrival rate and the distributions of parameters in buyers' bids are no longer known by the auctioneer. The simulations show that, compared to offline auctions (e.g., VCG), SALSA provides nearly optimal results in terms of efficiency and revenue, even without learning algorithms to determine the values of unknown parameters.

One important requirement of online auction is that there should be relatively high density of arriving asks and bids. Otherwise, there might not be enough liquidity in the auction market. For example, a bid may arrive at the auctioneer when there is no ask selling auction resources, thus the market cannot be cleared although the mechanism requires the auctioneer to clear the market immediately. A novel clearing algorithm in online auctions is proposed in [67]. The auctioneer dynamically decides the time to clear the market based on the optimal stopping theory [89], given that the asks and bids arrive stochastically. This approach neither requires the auctioneer to clear the market at fixed time as in an offline manner, nor forces the auctioneer to match asks and bids strictly in a real-time manner. Therefore, the algorithm can be best applied to the aforementioned system where high density of incoming asks and bids are not guaranteed.

4) Distributed Auctions: Conventionally, it is straightforward to have a centralized entity in the auctions for radio resource allocation. The centralized entity is used for conducting the auction, clearing the market, charging and receiving the payments. For example, the seller (i.e., auctioneer) in a single-sided auction [43], and the auctioneer between the sellers and buyers in the double auction [10]. However, some wireless systems may be partly or fully distributed systems without a centralized entity to manage the radio resource allocation. In such cases, distributed auction models can be applied.

In the case of a cognitive radio system with multiple primary users (i.e., sellers) and secondary users (i.e., buyers), each seller or buyer has multiple counterparts from the other side to sell/buy radio resources. As we mentioned, although double auctions are employed [9], the system in [9] still needs a centralized auctioneer. [12] removes the centralized auction controller and designs the double auction mechanism named multiauctioneer progressive auction (MAP). Each spectrum resource seller in the system independently seeks buyers within the coverage, and deals with them directly. Also, the buyers seek the sellers in the same manner. MAP works as follows. The seller starts by announcing a low asking price and gradually increases that asking price. When that price is attractively low, there will be more demand than supply, and the deal cannot be made. As the asking price keeps increasing and becomes less attractive to buyers, the demand from the buyers decreases. Finally, the demand and supply hit a balance, and then the auction terminates. MAP is proved to achieve the optimal allocation efficiency [12]. However, collusion and spectrum reuse problems are not considered in [12]. Lacking a centralized entity to manage the auction, sellers and buyers might collude in the auction. As a result, efficiency and sellers' total revenue could be reduced.

The fully distributed auction mechanism MAP [12] has a drawback that the communication overhead might be high, since MAP allows direct many-to-many communications between all the sellers and buyers. An auction mechanism proposed in [90] reduces such an overhead by applying a Dutch auction for distributed radio resource allocation. The Dutch auction has a "timing" feature working as follows. Before the auction starts, an initial asking price is set by each spectrum seller and informed to all the spectrum buyers. After the auction starts, that initial asking price decreases as a function of time. As such a function is known to all buyers according to the rules of the Dutch auction, the buyers can locally calculate the current asking price based on the presumed globally synchronized time. Once the buyer decides to accept the current price, then that buyer can make a bid by sending a message to the seller. The collision problem exists in the mechanism [90] if more than one buyer make bids at the same time. An arbitration algorithm should be further included in this design.

5) Combinatorial Auctions: As we mentioned in Section II-D, combinatorial auctions are usually employed in the situations that each buyer requests for a complete bundle of auction commodities. Even if only one commodity out of that bundle is not received, the buyer would be unsatisfied and have much lower utility.

[91] argues that combinatorial auctions had better be applied to the system with buyers who have combined requests for radio resources (i.e., time slots in [91]). Otherwise, a paradoxical "exposure problem" will emerge as follows. A spectrum user (i.e., auction buyer) auctions for a bundle of time slots from the resource seller to finish a communication task. Suppose that the user did not submit a combinatorial bid, it would have ended up with successfully receiving only a part of requested time slots. This is because the rest of the requested time slots might be so expensive that the user could not afford them. Therefore, the part of requested time slots that the user had already received finally became worthless, because they could not form a whole bundle to finish the task. In another word, by employing combinatorial auctions, users can fulfill their bids for bundles of auction resources in an all-or-none manner. That is, each user either receives all or none of requested auction resources [39].

Combinatorial auction mechanisms may have drawbacks in terms of a communication overhead and market clearing complexity. To exactly express the combinatorial bids, bidding languages with complex structures [13], [48] have to be used, which exponentially increase the size of bidding messages in the worst case [13]. The complexity of clearing the market is caused by the complexity of the combinatorial bidding requests. The clearing (i.e., allocation and pricing) process is NP-hard for the auctioneer in a combinatorial auction [13], [39]. To solve the complexity problem, approximation clearing algorithms are applied to produce sub-optimal results. For example, [91] proposes a practically solvable algorithm that leads to an approximation allocation result in terms of users' total cost (payment). That approximation result is constrained within the factor $(1+\log m)$ of the optimal result solved by the original NP-complete problem, where m is the total number of time slots (i.e., auction commodities).

B. Auctions for Transmit Power and Signal to Interference-plus-Noise Ratio (SINR)

Apart from subchannels and time slots, different power or SINR levels are traded as auction commodities in some radio resource auctions (i.e., power auction for short).

According to [85], the auctions for transmit power and SINR levels have different properties from that of subchannels or time slots. The users' transmission tasks via different subchannels or time slots do not interfere with each other. However, in the power auction models (take [85] as an example), wireless users share the same channel and receive different power levels (downlink) or use different power levels to transmit (uplink). Therefore, the users with higher power levels will suppress and cause interference to the users with lower power levels. Low power leads to low channel capacity for the user to transmit, so that each user naturally has incentive to participate in the auction and make bids for higher power levels. Another constraint of power auctions also exists. Once the purchased power level is lower down below a tolerable threshold, the users will not be able to transmit due to interference from any other users. The centralized auctioneer (or other controllers) has to include interference as a constraint when deciding the allocation schemes, which guarantees that each user will at least receive a usable power level above the threshold.

[49] and [73] propose single-sided power (or SINR) auctions. [49] discusses transmit power allocation in CDMA downlink channels. The core auction mechanism is a one-shot multi-bid auction as initially mentioned in [92]. A wireless user (i.e., buyer) who requests the power to transmit sends a set of 2-dimensional bids, each of which contains a power level and the buyer's bidding price for that power level. Thus, the multi-bid submitted by the buyer is the buyer's demand curve indicating that buyer's bidding prices for different acceptable power levels. Moreover, to satisfy the mobility requirement, users are allowed to update their bids dynamically during the auction [92]. This update process consumes extra channel resources, so that a fee must be charged to the users who execute the update. [73] designs an auction mechanism for power and SINR level. The classic VCG auction mechanism is abandoned in [73] due to high complexity in measuring channel gains by each user and solving the optimization problem for allocation. A rather simple auction is proposed that the auctioneer simply allocates the power or SINR level to the users proportional to each user's bid. Despite the simple design, the proposed auction mechanism in [73] can yield allocation results close to that of the VCG auction. However,

truthfulness is not considered in [73], and users have chance to lie about their true valuations in that simple auction.

[25] extends [73] into a double-sided power auction with multiple primary users (i.e., sellers) and secondary users (i.e., buyers). Secondary users in [25] can either transmit over the dynamically allocated channel (namely free spectrum channel) or the statically licensed channel. The free spectrum channel is not divided into subchannels or time slots. Therefore, as in [73], all the secondary users may transmit concurrently at different power levels over the single free spectrum channel. Each secondary user in this transmission will cause interference to other secondary users. However, in [25], each secondary user may not always stick to the dynamically allocated channel. Instead, secondary users may either join the auction for the free spectrum channel to save expenses, or pay (more) license fees and transmit over licensed channels with guaranteed QoS. It is observed that a ping-pong effect can happen that users may constantly switch between the free spectrum channel and the licensed channel. A no-regret learning algorithm is used to eliminate that ping-pong phenomenon, and the equilibrium of the auction can be reached. Furthermore, [25] presents numerical results to show the convergence process, efficiency and fairness of the proposed power auction.

C. Auctions in Joint Radio Resource Management Systems

Wireless network users may be exposed to different co-existing wireless network services in the same area, e.g., WLAN, CDMA, and Blue-tooth. This is the case of joint radio resource management (JRRM) systems [93]. The architecture of JRRM systems is provided in [87]. In a JRRM system, resource owners (i.e., sellers) such as base stations own different types of wireless services for network users (i.e., buyers) to access. Auctions can be applied to allocate those different wireless services from the sellers to the buyers.

[32] discusses a single-sided auction for wireless network services. There is only one service provider in the system, who provides and controls several co-existing wireless access networks within a certain area. These services are different in QoS. The VCG auction is applied to the system for network users (buyers) to compete for those services. Similar to [86], a double-sided auction model for JRRM systems is proposed in [87]. The auction market in [87] is controlled by a centralized regulator. Operators who work as service providers to terminal users (e.g., cell phones). There are different wireless network services offered by operators. Each operator may act as a radio resource seller or buyer, depending on whether the operator wants to sell out its own available network services or buy in other operators' services. Simulation results in [87] show that the auction-based model significantly increases the total radio resource utilization and revenue, comparing to a non-auction method.

VI. AUCTION APPROACHES IN MULTI-HOP NETWORKS

The previous section mainly discusses auction approaches applied in wireless networks with single-hop connections. In this section, we will survey on important works on auctions for multi-hop wireless networks, such as mobile ad hoc networks (MANETs), wireless mesh networks (WMNs), and wireless sensor networks (WSNs).

A. Auctions for Optimal Transmission Paths

1) Path Auctions in Mobile Ad hoc Networks: As aforementioned, auctions for an optimal path (namely, path auctions) are intuitive models of resource allocation in multi-hop wireless networks. A path auction with source nodes as buyers generally includes two steps. The first step is route discovery and selection. In this step, topology and transmission paths of the whole network are to be discovered. The second step is data transmission and payment transaction. A data message is transmitted from the source to destination nodes through the optimal path, and payment is made by the source node to the relay nodes along the chosen optimal path as the rewards to their cooperation.

[34] proposes a VCG based cost-efficient mechanism named an ad hoc VCG. Firstly, nodes exchange information of energy emission levels (power levels) with adjacent nodes, thus the topology graph is discovered and the optimal cost path can be calculated. The payment to transmit along the optimal path can be settled using the VCG algorithm. In the second step, the source nodes send data messages only along the optimal paths with the payments made to the relay nodes. However, in [34], the source and destination nodes of transmission are not considered as active and rational auction participants. That is, according to the mechanism, the source nodes have to unconditionally transmit and make payments after the optimal paths are selected, no matter how unreasonably high the prices are. [94] eliminates that assumption of irrational source nodes in [34] with new mechanism COMMIT (indicating commitment). The COMMIT mechanism takes each source node as a rational player, who has a reserved valuation. Once the price of optimal path exceeds the reserved valuation, the source node will refuse to transmit. A destination node is still not a player in [94], but treated as a neutral component (i.e., sink) of the system.

[95] aims to develop an auction mechanism to encourage cooperative data message relaying, named AIM (Auction Incentive Mechanism). In this auction, the node which currently needs to send a data message is viewed as a buyer, while the other available nodes within that buyer's transmission range are sellers. At every hop, the buyer node is willing to pay different prices to the adjacent seller nodes for relaying the message. The price for relaying is based on the location (whether on optimal path or not) and the energy level of the relay seller node. The relay nodes with higher energy levels and less ETX (i.e., expected transmission count metric measures the potential hop count of each node) [96] will ask for lower prices, due to low marginal prices. This may contradict the immediate idea that the auction commodity in better conditions should worth more money. Yet, the philosophy of the pricing scheme in [95] is possibly a "small profit but quick return" way. As described above, the proposed auction in [95] is a reverse English auction that the seller nodes compete to attract the buyer. The Bayesian Nash Equilibrium solution is proved to exist. After a series of such auction games are performed hop by hop, data messages are routed

from sources to destinations with the minimum costs. The simulation shows that AIM reduces failure rate of transmission as well as guarantees throughput of the system comparing to a conventional non-auction approach.

2) Peer-to-Peer Systems: Peer-to-peer systems require users to be cooperative and generous in sharing data. However, the peers in the system are essentially selfish since they belong to different owners. Auctions provide motivations for those selfish peers to share distributed data by providing rewards based on their sharing contributions.

[97] takes the lead in employing auction mechanism in mobile peer-to-peer networks by introducing a reverse auction model named ABIDE. The process is rather simple that a peer node (i.e., buyer) who requests some certain data broadcasts the queries to all other accessible peer nodes (i.e., sellers). Then, all the peer nodes, who have the data, report their ask prices and route information back to the buyer peer node. The buyer chooses the seller that is optimal to receive the requested data and makes a payment accordingly. Different from [34], the buyer peer node in [97] does not need to pay any money to the relay peer nodes along the transmission path. Instead, the relay peer nodes forward and keep a copy of the data, in the hope of selling the data later to other buyers. This is the economic incentive for peers to relay data. Moreover, a load balancing problem in peer-to-peer systems is also considered in [97]. Once a seller peer node is crowded with too many requests from buyers, that seller can copy the popular requested data to other peer nodes, thus to balance the network load. Experiments show that ABIDE outperforms traditional non-economic peer-to-peer models in terms of average response time of resource, requested data availability and average querying traffic in the network.

B. Auctions for Subchannels in Multi-hop Networks

Apart from auctions for optimal paths, the auctions for subchannels (i.e., bandwidth) in multi-hop wireless networks are also discussed in some typical works as follows.

An early work [33] presents a generalized Vickrey auction model for mobile ad hoc networks, named iPass (i.e., incentive comPatible Auction-based Service Scheme). The system architecture and auction rules are set up. The resource buyers are defined as the data flows passing through the same node (router) at the same time. The payments are carried along with those buyers (data flows) using a virtual currency as in [34] and [43]. The auction process is running on the router node (i.e., auctioneer), who allocates the subchannels to the buyers. It is shown that the auction mechanism works both as an incentive for the router nodes to share the resource, and a flow control method in a non-cooperative mobile ad hoc network.

[37] also discusses an auction model for the scenario that multiple data flows share the bandwidth (channel). However, in this case, the source node of those data flows are viewed as buyers to auction for the bandwidth divided into units (e.g., subchannels and time slots). Two distributed auction approaches are proposed, i.e., an ordinary auction mechanism, and a coordination auction where the buyers are updated with the recent bandwidth allocation information. [37] especially examines the impacts of nodes mobility on the system performance when running the proposed auction mechanisms. Simulation results of throughput and end-to-end delay of the system under different node moving speeds are shown that the two proposed distributed auctions achieve very close results to the optimal performance by a centralized linear programming approach [98].

[99] uses a VCG auction with network coding to improve throughput of multi-hop wireless networks. Network coding is applied in wired peer-to-peer networks for transmission of co-existing dataflows simultaneously [100]. By using network coding, a network user can code messages targeting different destinations into one packet and broadcast it to avoid to access the channels repeatedly. In the auction process, network users (i.e., buyers) make bids to the other nodes (i.e., sellers) with channel resources for channel access. The capacities of channels to be sold are limited by the sellers in the discussed scenario. As a result, the size of messages to be transmitted by the buyers are also constrained. The network coding technique is employed to achieve higher throughput of the network despite the capacity constraints. Numerical results show that, regardless of the number of network users in the system, social welfare can be significantly improved by using the proposed network coding mechanism, comparing to the non-auction mechanism and the mechanism without network coding.

Wireless sensor networks (WSNs) are discussed in [101], [102]. An auction is employed as a method to efficiently utilize resources at the congested nodes. The cause of congestion is due to the sensor data aggregation. That is, data messages in the wireless sensor network are usually forwarded to a certain destination (i.e., sink) which is used to collect and process those data messages. Thus the congestion may happen at this bottleneck destination. In [101], [102], data messages passing through and congesting the sensor node are defined as buyers, and the node that messages passing through can be seen as an auctioneer. Data messages are generated inside nodes (i.e., sensors), carrying local information and being routed to the destination. The value of each data message is based on the quality of the detected information. It is more profitable for the auctioneer to let the messages with high information quality pass the auctioneer node. However, the quality of information that the message carries will only be known at the destination after the data message is processed. Such quality of information can be expressed as the distance of the sensor to the object it monitors (i.e., precision). Furthermore, sensors are moving over time. As a result, the auctioneer has to decide the *ex ante* precision of the sensors from time to time *before* the messages arrive at the auctioneer. A predication-based algorithm is used in [101], [102] that the precision parameter is a linear function to the sensor's moving time, and the coefficient of the linear function can be known by the auctioneer empirically.

VII. OPEN ISSUES

As we have seen from the previous sections, auction theory serves as an effective interdisciplinary method to model the resource allocation processes in wireless networks. Besides the existing approaches, there are still some open research issues as follows:

- *Joint resource auction*: Most available studies on auctions for resource allocation in wireless networks are only based on a single type of auction commodities, such as subchannels or time slots. In practical systems, network users require multiple types of resources as auction commodities to satisfy QoS constraints in transmission. For example, the network users (i.e., buyers) may need to transmit packets over some subchannels at a certain power level. In this case, the subchannels and power levels are both auction commodities. Combinatorial auctions might be a possible way to model and solve this problem.
- *Seamless combination of auction and other approaches*: Most of the aforementioned works consider only an auction alone to solve the radio resource management problem. However, some papers suggest alternative solutions (e.g., as discussed in [26], [98]). In the hope of achieving better resource allocation results or more flexible schemes, the advantages of auction methods and other non-auction methods might be combined together. For example, suppose there are a large group of buyers in the system, several rounds of auctions can be adopted to obsolete most disqualified buyers. The remained buyers can negotiate to reach the deals.
- *Payment and settlement security*: The payment process in the auction for radio resource allocation is crucial. That is, the messages including payment information can be received by other irrelevant network users, among which there could be malicious users. Therefore, the security problems should be analyzed, and the techniques to protect the payment must be developed. Furthermore, in the central bank model [42], the neutrality of the centralized node who manages the payment accounts of all users is critical and needs to be ensured. There could be moral hazard problem, i.e., the central bank might be controlled by an untrusted entity and might default or violate network users' benefits.
- *Complex market and brokerage design*: In a traditional auction, there are usually three types of participants: buyers, sellers, and auctioneers. Buyers always purchase commodities from sellers with the help of auctioneers. However, in a more complex market, the trades can be made among buyers via an auctioneer, or between sellers and buyers directly, or even among auctioneers. Also the radio resources that are sold have chances to be bought back, forfeited or lent. Future works can be done on such diversified and intricately structured market for radio resource auctions.
- *Financial derivatives of auction commodities*: Radio resources in the auction approaches we surveyed so far are almost traded as spot commodities. The buyers must pay real/fictitious money and receive the resources immediately, i.e., direct payments on delivery. Derivatives are designed as a financial tool for commodity trading, and can be applied to radio resource auctions. For example, one type of such financial derivatives works as follows. A participant (either buyer or seller) is allowed to submit a contract, indicating that the participant will sell or buy a certain amount of radio resources at some time in the future. Therefore, the participant can "lock" the current price for the future trading and delivery. Having done that, the risk of losing profit is limited even the price becomes volatile in the future, due to the strategically locked trading price. In this process, the participant does not necessarily sell or buy the actual resources at the time of delivery, since the contract can be canceled before actual delivery by signing another reversed contract. This kind of financial derivatives promotes the flexibility of the radio resource auction market.
- *Auctions for other specific systems*: Auctions are less discussed in wireless networks other than cognitive radio and mobile ad hoc systems, such as machine-to-machine systems [103], vehicular networks [104] and cloud computing systems [105]. Auction can also be applied to these systems as the resource sharing method. Take *mobile cloud computing* as an example, mobile cloud is a promising way to enhance the computational capacities of mobile users by having large scaled computational resources (i.e., cloud resources) as the backbone. Cloud resources are packed into standard services, which can be sold as auction commodities. The participants of the market might be defined as follows. *Cloud providers* consist of both large cloud computing service providers (i.e., Google and Amazon), as well as small-scaled cloud providers. *Cloud retailers* are the mobile telecom companies, who buy and integrate cloud resources from different cloud providers, and sell them to the end *mobile cloud users* and other immobile users. The marketplace that the cloud providers and retailers trade cloud resources is defined as an *exchange for cloud resources*. The core mechanism running in the exchange for trading is still an auction. In this system, the cloud providers, cloud retailers and the exchange form a *wholesale cloud market*. The market between the cloud retailers and normal mobile cloud users is defined as a *retail market*.

VIII. CONCLUSION

We have presented a survey on auction theory and its applications in wireless networks. Firstly, we have provided an overview of the fundamentals, theories and general objectives of auctions. Then we have introduced the motivations and detailed techniques to apply auction models to resource allocation problems. Afterwards, we have surveyed some recent works on auctions in single-hop and multi-hop wireless systems as examples of auction approaches in radio resource management of wireless systems. Finally, several open issues on auction-based design of cognitive radio systems have been outlined.

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