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Combinatorial auction based spectrum allocation under heterogeneous supply and demand

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ABSTRACT

In this paper, we apply the combinatorial auction scheme to solve the spectrum allocation problem under heterogeneous supply and demand in cognitive radio networks. The heterogeneity of spectrum is embodied via exploiting multiple attributes, based on which a valuation function is devised to evaluate the preference of an SU over a spectrum band. We first propose an auction scheme consisting of a greedy-like winner determination algorithm and a critical value based discriminatory pricing policy. We then extend the proposed auction scheme to a more challenging scenario by considering spectrum sharing among SUs. Theoretical analysis demonstrates that our auction schemes achieve individual rational, budget balance, value-truthfulness of SUs, and weak value-truthfulness of PUs. Our simulation results verify the advantage of combinatorial auction, the functionality of spectrum sharing and the economic robustness of our auction schemes.

1. Introduction

With a rapid growth of wireless devices and applications, the ever-increasing spectrum demand poses a great challenge on current fixed long-term spectrum allocation schemes. Cognitive radio [1] which utilizes spectrum holes by permitting opportunistic access, serves as a promising technology to alleviate the scarcity of spectrum resource. Opportunistic access asks Primary Users (PUs), who own the licensed spectrum bands, to temporarily release their spectrum resource to Secondary Users (SUs), who desire the spectrum for transmission.

A main challenge lying here is to provide incentives for PUs to share their spectrum resource. Motivated by this, many researchers paid their attentions to the economic aspect in cognitive radio networks. Many popular economic tools such as price [2], game theory [3], contract theory [4], and auction [5], have been widely applied. Among all the economic tools for spectrum allocation, auction is the preeminent due to its fairness and efficiency. Various forms of auction have been brought to the research, such as VCG auction [6], McAfee auction [7], and Walrasian auction [8]. A critical issue in studies on auction is economic robustness, since it is necessary to keep the auction invulnerable and avoid market manipulation. The economic robustness requires auction participants to satisfy three most common economic properties (detailed in Section 3.2).

Though many studies on auction based spectrum allocation have been proposed, two important aspects in spectrum trading have been overlooked. First is the heterogeneity on spectrum supply and demand. In a realistic network, spectrum bands offered by PUs are often heterogeneous on bandwidth and available duration, due to, for example, the diversity of PUs' activities. Meanwhile, the demands of SUs on bandwidth and using time also show the heterogeneity since SUs may have different kinds of applications. However, previous works either ignore this aspect by assuming all the channels are identical and SUs only care about how many channels they obtain [9–11], or only focus on a single attribute which cannot fully reflect the heterogeneity of supply and demand [12–16].

Second, in traditional auction, buyers are only allowed to bid for an individual item, which greatly restricts the flexibility of requirement and compromises the efficiency of allocation result. Combinatorial auction [17] allows the buyer to bid any combination of items, called "a bundle", rather than just an individual item. Through combinatorial auction, buyers can fully express their preferences towards the items, which is able to enhance the efficiency of allocation result. However, few of previous works concentrates on this kind of auction.

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In this paper, we intend to design a combinatorial auction based spectrum allocation mechanism under heterogeneous spectrum supply and demand while guaranteeing the economic robustness of both SUs and PUs. To tackle these problems, we first introduce an attribute based valuation function to evaluate the preference of an SU towards a specific spectrum band, through which SUs can form their auction bids. After that, we design a combinatorial auction scheme consisting of a greedy-like winner determination algorithm and a critical value based discriminatory pricing policy. To further enrich the flexibility, we consider the spectrum sharing among SUs and design a multi-round auction scheme under this modification. We provide theoretical analysis on both two schemes to show the guarantee of economic robustness. Finally, we conduct an extensive simulation to evaluate the performance of designed schemes.

The rest of this paper is organized as follows: Section 2 briefly summarizes some of the related literature. Section 3 introduces the network model, problem formulation and economic properties. Section 4 presents the attribute based valuation function and the concept of spectrum combination. The details of two auction schemes and theoretical analysis of economic properties are described in Sections 5 and 6. Section 7 presents the simulation results and Section 8 concludes the paper.

2. Related work

In this section, we summarize some of the relevant works on spectrum auction.

Zhou et al. [10] propose a truthful double auction scheme called TRUST, which enables spectrum reuse and achieves economic robustness. The paper assumes that each PU only supplies a single spectrum channel and each SU only demands one. Xu et al. [11] extend the TRUST to a multi-unit auction, in which each PU/SU can supply/demand multiple channels. However the authors do not consider spectrum reuse. Jing et al. [9] combine multi-unit auction and spectrum reuse together. The authors propose a concept of virtual node, i.e., a node with multi-unit demand can be viewed as multiple virtual nodes with single-unit demand. Virtual nodes form the conflict-free groups among which the spectrum channel can be reused. Xiang et al. [18] propose an auction scheme with discriminatory pricing, which is different from the uniform pricing in former three schemes. Huang et al. [19] take user bids into consideration in the stage of group formation. Wang et al. [20] provide a flexible spectrum bidding via supporting range requests and strict requests. However, all these works assume that spectrum channels are identical.

The heterogeneity on spectrum channels is considered in [12,13]. They both assume that different channels have different carrier frequencies, which may cause non-identical conflicts among SUs because different frequencies have distinct communication ranges. This heterogeneity only impacts the formation of conflict-free groups and is not reflected in SUs' demands. Refs. [14–16] take the demand on time dimension into consideration via studying online auction design, where demands/supplies are arrived in an online fashion. Spectrum reuse in spatial domain is considered in [15,16] and spectrum preemption is allowed in [14]. Nevertheless, spectrum demand on both time and bandwidth has never been considered in these works.

Recently, another attractive direction of spectrum auction in cognitive radio networks is the usage of combinatorial auction, where each SU can request for any combination of items rather than a single one. Forde et al. [21] trade spectrum rights in an OFDMA-based network through combinatorial clock auction, in which the final assignment is driven by varying item prices. Xu et al. [22] propose a reverse iterative combinatorial auction for spectrum allocation in D2D communication systems. The D2D link is viewed as an item while spectrum resource is viewed as the buyers. Dong et al. [23] propose a truthful combinatorial auction. The spectrum resource is divided into uniform time–frequency blocks, and SUs bid for a set of blocks, either consecutive or discrete. All above works on combinatorial auction fall into the scope of single-side auction, in which the economic properties of PUs has not been considered.

Despite all the previous works, the problem of designing a combinatorial double auction based allocation mechanism with heterogeneous spectrum supply and demand while guaranteeing the economic robustness of SUs and PUs has not been addressed. Here, we tackle this problem.

3. Preliminary

3.1. Network model

In this paper, we consider a spectrum market consisting of M secondary users, denoted by $SU_1, SU_2, \ldots, SU_M$ ($SU_i \in \mathcal{M}, 1 \leqslant i \leqslant M, M = |\mathcal{M}|$), and N primary users, denoted by $PU_1, PU_2, \ldots, PU_N$ ($PU_j \in \mathcal{N}, 1 \leqslant j \leqslant N, N = |\mathcal{N}|$).[1] $\mathcal{M}$ and $\mathcal{N}$ represent respectively the set of SUs and PUs. There is a control centre acting as the auctioneer in auction scheme.

We assume that each PU supplies a spectrum band which can be divided into multiple orthogonal subchannels. The attributes of PU_j's spectrum band are denoted by $\{n_j, w_j, s_j, d_j\}$, indicating that PU_j has n_j subchannels, and each subchannel has a bandwidth of w_j and can be continuously used from the starting time s_j to the ending time d_j. We assume the attributes of PUs' spectrum bands are generally public, indicating that PUs do not report fake attribute info to the auctioneer. Such an assumption is adopted by [24]. Each PU has an intrinsic cost for its spectrum band, denoted by c_j. The cost information is private, which means a PU may or may not report its true cost to the auctioneer.

On the other hand, an SU needs to require proper spectrum resource to satisfy its transmission demand. Specifically, the attributes of SU_i's spectrum demand are denoted by $\{B_i, s_i, d_i\}$, indicating that SU_i wants a spectrum band with a bandwidth of B_i and can be continuously available within $[s_i, d_i]$.

3.2. Problem formulation and economic property

We model the allocation process as a spectrum auction, in which PUs are sellers and SUs are buyers. At the beginning of the auction, each PU sends spectrum information to the auctioneer, including the spectrum attributes and its ask price. The auctioneer then broadcasts the attributes to all SUs. After receiving the spectrum attributes, each SU chooses its favorite spectrum band to bid. To provide bidding flexibility, we introduce the concept of combinatorial auction which allows SUs to bid for a bundle of bands from different PUs. The bid information is sealed and each SU has no knowledge about others. At last, the auctioneer conducts the auction to determine spectrum allocation and the payment.

Let $\mathcal{M}_w$ be the set of winning SUs and $\mathcal{N}_w$ be the set of winning PUs. Let p_i be the price that winner SU_i needs to pay and p_j be the price that auctioneer pays the winner PU_j. Then the utility of buyer SU_i ($SU_i \in \mathcal{M}$) can be calculated as

$$U_i = \begin{cases} v_i - p_i & \text{if } SU_i \in \mathcal{M}_w \\ 0 & \text{otherwise} \end{cases} \tag{1}$$

[1] Throughout the paper, we use subscript i and j to denote the notations associated SU_i and PU_j, respectively.