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Group buying spectrum auction algorithm for fractional frequency reuse cognitive cellular systems

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ABSTRACT

Fractional frequency reuse (FFR) can not only coordinate inter-cell interference (ICI), but also improve communication quality of cell-edge users, whose key idea is to make a tradeoff between frequency utilization efficiency improvement and ICI suppression. In terms of the fact that conventional spectrum auction neglects the inter-cell and intra-cell interference and wireless spectrum has become scarce resources in cognitive radio networks, in this paper, FFR technology is introduced into the field of spectrum auction and a group reuse spectrum auction mechanism for FFR (GRSAF) is proposed in cognitive cellular systems to achieve higher spectrum allocation and usage efficiency. A Lagrangian relaxation (LR) algorithm is developed to solve the optimal sum utility maximization spectrum allocation problem. Simulation results show that the GRSAF mechanism can significantly improve the sum utility, spectrum reusability as well as satisfaction degree of buyers compared with other two existing auction mechanisms.

1. Introduction

With the rapid deployment of cognitive radio networks, the precious spectrum resource is becoming increasingly crowded. Besides, the requirement for radio spectrum usage has growing rapidly with the dramatic development of the mobile telecommunication industry in the last decades [1–5]. Meanwhile, it is well known that the existing spectrum allocation policies usually lead to inefficiency on spectrum utilization, which is called “white space”, due to its static spectrum allocation manner. Hence, more effective spectrum allocation and utilization schemes are urgently required for the next-generation wireless networks [6]. In order to effectively use white spaces, a promising method is to realize frequency reuse. That is to say, the licensed primary users (PUs) lease their unoccupied spectrum to the unlicensed secondary users (SUs) and in return, the PUs can get corresponding revenue from SUs [6]. The problem of spectrum reallocation and reutilization between multiple PUs and SUs can be modeled as a spectrum auction game, which is a process of buying and selling spectrum resources through offering PUs’ asking bids, submitting SUs’ bids, and selling items to the winning bidders [7].

Auction has been widely applied to spectrum allocation and has obtained some huge achievement recently. For example, in simple forward auction, spectrum reusability was applied by assigning the same spectrum to non-interfering buyers [8]. In order to guarantee truthfulness, in double auction, a third-party auctioneer is needed [9]. The authors in [10] indicated that dynamic spectrum auction has been considered as a promising approach to effectively reallocate spectrum resources in the secondary spectrum market. Besides, a combinatorial auction with flexible bidding formats was proposed in [11] for the channel allocation problem in cognitive radio networks. Moreover, the current research works and literatures have studied revenue maximization auction [12], truthfulness guaranty auction [13–16] and flexible auction [17]. As we all know that a classic auction which can guarantee truthfulness is the celebrated VCG mechanism, but the vulnerabilities of the VCG mechanism are so severe that it is seldom applied directly in the reality [18]. In addition, while those auction mechanisms can achieve an optimal allocation, they did not capture the interference as well as collusion problem systematically. To address the challenges, a location-aware online double auction mechanism in [19] was proposed to handle the interference problem while the buyers locate in a critical place. The author in [20] investigated a truthful group buying-based auction to take advantages of the collective buying power of secondary users within each secondary network. The scholars in [21,22] also proposed a scalable collusion-resistant multi-winner spectrum auction, in which the collusive behavior of selfish users was carefully taken into consideration. Unfortunately, all of the above works only considered exclusive usage model and simply assumed that there was no inter-cell and intra-cell interference among all auction participants. It is highly unrealistic in practical spectrum sharing systems. Beyond that, the spectrum access rights of each user relies on their Quality of Service (QoS) requirements and it is desirable

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to allocate spectrum access rights on the basis of QoS demands as well as to exploit the resulting spatial spectrum reuse opportunities [23].

Although those above-mentioned auctions ensured benefits of the system, none of them can support frequency reuse while preserving other performance such as truthfulness [24], so the spectrum reusability is still inefficient. On the other hand, the spectrum resource is interference-limited rather than quantity-limited, therefore it is critical and difficult to mitigate interference problems. Furthermore, the interference between inter-cell and intra-cell has not attracted enough attention among past researches. In [25], the author illustrated that the inter-cell interference problem was a key issue in cellular networks and users at the cellular border would suffer from high inter-cell interference. Therefore, the signal strength will be weaken if the interference cannot be handled well. Although the authors in [26] proposed an extensive analysis on interferences, they still neglected the inter-cell and intra-cell interference when two SUs used the same spectrum, so the QoS of SUs is worth re-considering, especially the cell edge users' QoS cannot be guaranteed.

FFR, a recent emerged wireless networks technology, is an effective and promising approach to tackle the interference problem in cellular systems [27]. The main thoughts of FFR are to divide the cell bandwidth into center and edges so that cell edge users do not interfere with each other. What's more, it can mitigate the interference to interior users created by cell edge users and achieve a more efficient spectrum utilization than other traditional frequency reuse methods. In recent years, FFR has been widely used in managing the co-channel interference as well as improving spectrum reusability through frequency reuse factor (FRF) within LTE-advanced Networks, Heterogeneous Cellular Networks and Distributed Antenna Systems (DAS) [28]. In addition, the author in [29] proposed a spectrum swapping allocation solution for the femtocells over-sailed by the FFR aided macro cells for the sake of overcoming both the adverse near-far effects and the cross-layer interference. The authors in [30,31] contributed to design optimal FFR schemes and they solved the interference coordination problem already. Furthermore, FFR can improve spectrum utilization through different choice of FRF values. Generally, FRF 1 is the best choice in terms of cell throughput, but it causes serious interference to the cell boundary, so it is unable to serve the whole cellular area. Therefore, some researches today choose FRF value greater than 1. Mitran et al., in [32] devoted to design flexible FRF so as to achieve a higher spectrum reusability. They developed a flexible FRF design mechanism and provided an intermediate value between 1 and 3 as FRF while the conventional schemes dedicated to use some integer numbers such as 1, 3, 4, or 7. In fact, some typical hexagonal cellular model always choose FRF 3 to analyze their system [33].

To the best of our knowledge, this is the first work to investigate the spectrum auction mechanism combined with spectrum reusability and FFR technique together. In our design, the interference risk and spectrum reuse are taken into account simultaneously. Besides, in order to take both advantages of FFR and spectrum auction, a group reuse spectrum auction mechanism based on FFR (GRSAF) are developed and a Lagrangian relaxation (LR) algorithm is designed to solve the optimal spectrum allocation problem eventually. The major contributions of this paper are summarized as follows:

- We propose a group buying spectrum auction mechanism based on FFR, which makes a tradeoff between spectrum utilization and spectrum reusability.
- The proposed spectrum auction mechanism can restrain the co-channel interference effectively.
- A LR algorithm is developed to achieve optimal allocation of spectrum resources.

The rest of this paper is organized as follows. In Section II, we describe the spectrum auction preliminaries. In Section III, the spectrum auction model based on FFR is introduced and the design of the group buying spectrum auction mechanism with a LR algorithm is presented in detail. Except that, the performance evaluation through numerical simulation is presented in Section IV and finally, the conclusion is made in Section V.

2. Spectrum auction preliminaries

A well-designed spectrum auction mechanism should not only be truthful, but also be individually rational, budget-balanced and efficient in terms of spectrum utilization [6]:

(1) Truthfulness: Since the SUs are rational and they always want to maximize their own profits, so it is likely that they would strategically dissimulate their true valuations. Truthfulness is that SUs cannot benefit from concealing their true valuations.
(2) Individual rationality: That is to say, sellers are paid no less than their ask valuations and buyers do not pay more than their true bids.
(3) Budget-balance: The total amount of prices that buyers have to pay are no less than the total amount of reward received by the sellers. It can guarantee benefits of the auctioneer who runs the auction.
(4) Efficiency: It is the difference of total valuations between winning buyers and sellers. What is more, a higher efficiency is achieved by selling the spectrum resources to the buyers that value most.

Spectrum auction in cognitive radio system is different from conventional auctions as it has to address the interference among PUs and SUs. Next, we will elaborate the impact of inter-cell and intra-cell interference while fully considering the above performance. Meanwhile, the premise of achieving optimal spectrum allocation is to maximize the system utility. This is a non-cooperation game where all players try to minimize their own cost function under the strategies of other participants. Besides, whether there is an optimal solution depends on the existence of a Nash equilibrium. So convergence analysis of the above game is needed and the commonly used criterion is Nash equilibrium.

3. System model and problem formulation

In this section, we first introduce the cognitive cellular system model. Then, a group buying spectrum auction mechanism based on FFR between spectrum owners and service providers is formulated in detail. Next, the auction mechanism is proposed as an optimal spectrum allocation problem and the Nash equilibrium of it is also analyzed. Finally, a LR algorithm is designed to solve it.

3.1. System model

Consider a FFR cognitive cellular system where the primary base station (PBS) and PUs locate at the center of cellular while SUs are deployed on the edge, as shown in Fig. 1. The number of SUs and PUs are N and K, respectively. It is closer to the practical application than a scenario where the number of PUs and SUs are only one. Furthermore, PUs and SUs are randomly distributed in a 7-cell system. For simplicity, we suppose that PBS, PUs and SUs are all equipped with a single antenna. The SUs share spectrum resources with PUs. Due to spectrum sharing, the interference between them is inevitable. Therefore, how to restrain and reduce

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