Full length article

A spectrum auction algorithm based on joint power control and beamforming in small cell networks

Feng Zhao, Yuyi Zhang, Hongbin Chen *

Key Laboratory of Cognitive Radio and Information Processing (Guilin University of Electronic Technology), Ministry of Education, Guilin 541004, China

ARTICLE INFO

ABSTRACT

Spectrum auction is considered as a suitable approach to efficiently allocate spectrum among unlicensed users. However, in previous studies of spectrum auction, competition can hardly be reflected in the traditional spectrum allocation and the spectrum efficiency is still not high after the allocation. In this paper, we enhance the factor of competition in the auctions, in which bidders need to pay for the competition and the interference to macro cell users (MUs). We consider a communication system with one macro cell and several small cells, thus a licensed radio spectrum is shared by both MUs and small cell users (SUs). A truthful auction algorithm is proposed for spectrum allocation and the spectrum is divided into multiple channels in different time slots, so that SUs can make their choice for bidding under the guidance of history. In order to raise the communication quality, we propose a power control and beamforming algorithm in the heterogeneous network to enhance the system performance. Simulation results are presented to verify the effectiveness of the proposed algorithm in the small cell network.

© 2017 Elsevier B.V. All rights reserved.

1. Introduction

Radio spectrum has become a scarce resource due to the rapid increase in wireless service demand. Recently, the spectrum auction is becoming an efficient way in spectrum allocation. A truthful quality of service (QoS) aware spectrum auction mechanism was proposed in [1], which figured out an effective auction needs to possess truthful and individually rational properties. The former guarantees no additional profit could be awarded for bidders by cheating while the latter ensures that the profit of each bidder is no less than zero, which incentivizes bidders to voluntarily participate in the auction. In [2], a new spectrum auction mechanism for the cognitive radio network with multiple primary spectrum owners and multiple secondary users were proposed. Each primary spectrum owner has multiple channels to sell while each secondary user can access multiple licensed channels to satisfy its specific spectrum demand. In a secondary spectrum market, a spectrum owner or primary user leases its idle spectrum channels to secondary users through auction. A natural goal of spectrum auction design is truthfulness, under which a secondary user's best strategy is to bid its true valuation of a channel, with no incentive to lie. Another important goal in spectrum auction design is social welfare maximization [3]. In [4], an approximate differentially private, strategy-proof, and polynomially tractable spectrum auction mechanism was proposed. In dynamic spectrum sharing

networks, secondary users without the licenses of using cognitive radio spectrum may opportunistically access and share the unused spectrum of primary users who have spectrum licenses on the premise that the primary user's services are not degraded [5]. And they designed a recall-based dynamic spectrum auction algorithm. Primary base station (PBS) divides its channels into two parts based on its current services state. One part is used by its own users while the other part is sold among some secondary wireless service providers for more revenues. As a reasonable protection of the PBS' users, the PBS' users are granted a higher channel access priority than the secondary wireless services providers, and then the PBS can recall some channels after auctions to satisfy its demand if necessary. [6] proposed a new, online auction framework to dynamically evaluate the true value of channels in each time slot, while maximizing the time-averaged individual utility and social welfare in the long run, under practical system dynamics. [7] was the first work to study spectrum auctions for allocating variable bandwidth spectrum to secondary users. The framework was constructed for variable bandwidth spectrum auction and was proved as system efficient. A truthful spectrum auctions with approximate revenue was proposed in [8], under the relaxed Bayesian setting where in the bidder valuations were drawn from publicly known probability distributions. And it is the first work to design polynomial-time truthful spectrum auctions that offer a constant-factor approximation to the social-welfare or the expected revenue.

The power allocation could be an effective way to prevent secondary users from increasing their transmit power selfishly. Highly energy-efficient power control scheme was necessary to

---

* Corresponding author.
E-mail address: chbscut@guet.edu.cn (H. Chen).

reduce the waste of energy [9,10]. In [11], the authors developed a distributed power control scheme for a full-duplex small cell network. And the authors proposed that a payment is needed to be paid by secondary users for the interference to primary users. The payment is set as the difference between the revenue of SUs and the cost of interference to primary users. [12] studied the power control scheme in small cell networks. The objective is to improve the system energy efficiency. [13] proposed a distributed energy-efficient power control algorithm for the uplink two-tier networks with small cells and massive MIMO. The distributed power control algorithm is implemented by decoupling the optimization problem into two steps for multi-user and multi-cell scenario. In [14], the authors investigated the power allocation for cognitive small cell network based on hybrid spectrum sensing. And the optimization of energy-efficient sensing time and power allocation was modeled as a non-convex optimization problem so that they solved the problem in an asymptotically approximate optimal manner. [15] proposed an algorithm with the optimal power allocation and beamforming scheme for the SU transmitters in the cognitive radio network. And they considered both perfect channel state information (CSI) and imperfect CSI in the simulation. [16] focused on scenarios based on full-duplex by optimizing power allocation. A cognitive radio enabled small cell network can further improve the system performance by co-existing with a macro cell network [17]. There were three ways for cognitive small cell to access the spectrum performance by primary macro cell spectrum sharing, opportunistic spectrum sharing, and hybrid spectrum sensing. And a novel energy efficient OFDMA cognitive small cell optimization framework was designed, which was a new approach by considering energy efficiency and cross-tier interference mitigation, imperfect hybrid spectrum sensing, and user QoS requirements in the design of OFDMA cognitive small cell optimization framework. [18] proposed that the multi-agent decentralized technology for reinforcement learning was applied to deal with the dense deployment. The reinforcement learning algorithm has been widely applied to solve various problems and the paper was the first work to apply this algorithm to solve the energy saving problem in small cell networks. [19,20] indicated that the small cell base stations with power allocation would provide dense space communication services through the small cell networks.

To the best of our knowledge, beamforming techniques can be used to reduce intra-layer and inter-layer interference. In particular, the high beamforming gain offered by the massive MIMO could be an essential improvement for small cells. Using beamforming in the spectrum sharing situation can be useful to compensate the path loss of signals and then raise the signal-to-interference-plus-noise ratio (SINR) efficiently. In [21], beamforming approaches in cognitive small cells and coordinated multipoint (CoMP) systems were presented. [22] established the system model of the joint beam selection and client association problem and proposed a practical efficient algorithm. In [23], a downlink beamforming algorithm with small cells in wireless heterogeneous systems was proposed. Due to different capabilities of macro cell base station (MBS) and small cell base station (SBS), MBS and SBS could support users differently [24,25]. And joint power allocation and beamforming could be used to increase the system utility [26].

In this paper, we study the problem of designing a truthful auction mechanism for spectrum allocation. In order to overcome the shorts of spectrum resources, cognitive radio is presented for spectrum sharing. The secondary users could share the access rights with the primary users. In our communication system, the MUs are the licensed users while the SUs are the secondary users. The spectrum auction mechanism can improve the enthusiasm of spectrum owners to share effectively. We present a truthful spectrum auction mechanism of multiple time slots in which bidders
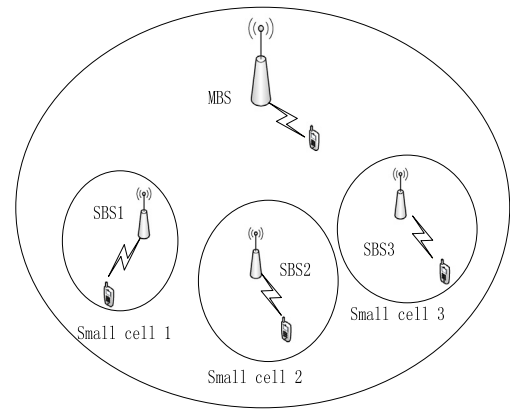

Fig. 1. System model.

could quote their price referring to information of channels in the last time slot. Then we jointly design the power allocation and beamforming. The simulation results show that the mechanism can effectively and efficiently improve the communication quality. The main contributions of this paper are as follows:

(1) We design a truthful spectrum mechanism in different time slots. Bidders need to pay for the rights to access spectrum and to the interference to primary users. The price they quoted is related to the history information.

(2) We jointly design the power allocation and beamforming after auction to prove that small cell base station individually increase the transmission power so that the interference would be restrained effectively.

The rest of the paper is organized as follows. Section 2 presents the system model and the transmission of the signals. The auction design and proof of truthfulness are introduced in Section 3. The algorithm of power control and beamforming is described in Section 4. Finally, the simulation results and conclusions are shown in Sections 5 and 6.

2. System model

The communication scenarios in this article is composed of a macro cell and many small cells. The small cells are low-powered cellular radio access with nodes that operate in licensed and unlicensed spectrum and have a range of 10 m to a few kilometers. They make best use of available spectrum by re-using the same frequencies many times within a geographical area. And the deployment of self-organized small cell networks is intend to increase system coverage and capacity. In the system, the users in one group are supported by small cell base station while the users in the other group are supported by macro cell base station.

The system model is shown in Fig. 1 and the transmission of the signals is shown in Fig. 2.

The users who are only covered by MBS is marked as MUs. And the users who are covered by SBS is marked as SUs. There are m MUs and k SUs in the communication system. And the SBS is equipped with multiple antennas. We assume the channel state information is known and does not vary in a time slot.

The signal received by the mth macro cell user is represented by

$$y_m = \sqrt{P_T} g_m z_m + \sum_{j=1, j \neq m}^{M} \sqrt{P_T} g_j z_j + \sum_{i=1}^{K} \sqrt{P_i} h_{pi} f_i x_i + n_p. \quad (1)$$

In this equation, z_m is the signal transmitted from the MBS to the mth MU. z_j is the signal transmitted from the macro cell base station to the jth MU, for which $j \neq m$. x_i is the signal transmitted