Computer Communications 97 (2017) 40–51

Contents lists available at ScienceDirect

Computer Communications

journal homepage: www.elsevier.com/locate/comcom

Auction-based resource allocation for cooperative cognitive radio networks☆

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ARTICLE INFO

Article history:
Received 16 April 2016
Revised 30 August 2016
Accepted 16 October 2016
Available online 3 November 2016

Keywords:
Cooperative cognitive radio networks
Auction
Resource allocation
Relay
Spectrum allocation

ABSTRACT

Cooperative cognitive radio network (CCRN) is a promising paradigm to increase spectrum utilization and exploit spatial diversity. The allocation of two coupled resources, *i.e.* spectrum and secondary relay nodes, plays a fundamental role in the performance of CCRNs. However, previous studies either lack of incentives for both primary users (PUs) and relay nodes to participate in or consider spectrum auction and relay auction separately. In this paper, we consider a static cooperative cognitive radio network scenario with several PUs and multiple secondary user coteries, each of which consists of a set of secondary users who are interested in sharing the same secondary relay node. We model the problem of joint spectrum allocation and relay allocation as a hierarchical auction and propose two auction schemes, *i.e.* TERA and UERA. TERA is the first Truthful auction mechanism for Efficient Resource Allocation in CCRNs which satisfies critical economic properties. UERA is an approximate truthful scheme which adopts a uniform price for fairness in the same secondary user coteries. Furthermore, we theoretically prove TERA and UERA can achieve near-optimal revenue. Finally, extensive simulation results show that TERA and UERA are efficient and able to improve the utility of PUs and relay nodes significantly.

1. Introduction

The proliferation of wireless devices and the rapid development of wireless communication applications have caused two critical challenges: one is the huge starvation for the valuable spectrum resources, and the other is the guarantee of Quality of Service (QoS) for wireless users. Recently, cooperative cognitive radio network (CCRN) [1] which leverages both the technology of cognitive radio and cooperative communication is shown to be a promising paradigm to solve those two challenges. By utilizing the cognitive radio technology [2], CCRN allows unlicensed users (secondary users, SUs) to dynamically access the licensed spectrum occupied by spectrum holders (primary users, PUs) to improve spectrum utilization, and with the technique of cooperative communication [3], wireless transmitters in CCRN can improve their transmission capacity dramatically by exploiting spatial diversity of relay nodes.

According to who serve as relay nodes and who are the benefited transmitters, researchers have proposed three kinds of CCRN paradigms. The first CCRN paridigm [44,47] is that primary users may select some of secondary users to be the cooperative relays, and in return grant transmission opportunities to those SUs. Noticing that primary users are generally considered to be able to support their target throughput alone and thus the cooperation from secondary users may has less attraction for PUs, Zou et al. [45] present a new CCRN paradigm, in which primary users will serve as relays for SUs to earn revenue. However, to ensure cooperation between PUs and SUs, complicated cross-lay designs [46] are usually required in those two paradigms. So, in this paper, we will consider the CCRN paradigm [37] that a secondary user chooses some other secondary users to relay its transmission data.

In our considered CCRN paradigm, secondary users who hunger for high transmission rate and high quality channels may contend for both secondary relays' access time and primary users' spectrum. Furthermore, a secondary relay node can cooperate with a secondary user only if they share a common spectrum. Therefore, the allocation of spectrum and secondary relay nodes are coupled and should be addressed jointly. Although numerous previous researches [1,4–6] have been conducted on this topic, those works assume that PUs and secondary relay nodes are willing to share their resources without reward which is not always practical. In reality, however, PUs and secondary relays are usually selfish and reluctant to share their resources for free, thus it is necessary to provide to participate in. A natural solution for this problem is to

☆ This is an extended and enhanced version of [36].

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http://dx.doi.org/10.1016/j.comcom.2016.10.013
0140-3664/

utilize the auction-based approach [7] for resource allocation in CCRNs.

The challenges for designing a practical and effective auction in our considered CCRN are two-fold. Firstly, the character that spectrum allocation and relay allocation are coupled makes the auction design for resource allocation in our considered CCRN paradigm special but challenging. Even though a large volume of researches have considered either spectrum auction [8–10] or relay auction [11–13] in the literature, those works can not be applied here because they do not consider spectrum auction and relay auction jointly. To our best knowledge, Han et al. [44] is the first to investigate auction-based resource allocation in CCRNs. However, they considered the paradigm that primary users choose secondary users as relays which is different with this paper. Secondly, a relay node usually can be shared by multiple secondary users in various situations [14–16], e.g. cellular networks or WLAN. Thus, a relay node may sell its access time to multiple SUs to improve its utility. However, it is a great challenge to allocate the access time efficiently while providing sufficient incentives for relay nodes.

To deal with the above challenges, we attempt to design an appropriate auction framework for allocating spectrum and secondary relays between SUs fairly and effectively. To be specific, we first assume secondary users are independent so that they can choose their desired secondary relays freely according to their preferences, and we call those secondary users who are interested in the same secondary relay as a secondary user coterie (SUC). Then, we let each secondary relay node play as a middle agent who takes charge of collecting bids from its corresponding SUC. According to SUC's bids, secondary relay node will determine its bid for spectrum. Afterwards, all secondary relay nodes contend for spectrum from PUs and winning relays will allocate both its gained spectrum and its access time to SUC. In the above procedure, PUs can gain payment from secondary relay nodes, and secondary relays can also gain financial compensation due to the surplus between its collected fees from SUC and its payment to PUs. So, our design can provide ample incentive for both PUs and secondary relays to participate in.

Under the aforementioned guideline, without loss of generality, we consider a static cooperative cognitive radio networks with several PUs and multiple secondary user coteries, each of which consists of a set of secondary users who are interested in sharing the same secondary relay node. To depict the character that a relay node can be accessed by multiple SUs in the same secondary user coterie, we assume that each SU has a valuation on that relay node and a budget constraint on the maximum payment it willing to pay. Specifically, the valuation represents the benefit that the SU gets when it accesses the relay node alone, while the budget determines the total access time that a SU can get from relay node which will be illustrated later. We model this problem as a hierarchical auction: First, each relay node collects bids from the corresponding SUC and conducts a virtual auction to allocate its access time to the SUs in that SUC. Next, a double auction is conducted between relay nodes and PUs to determine the allocation of spectrum. Finally, the winning relay node will perform the auction result in the first step to allocate the spectrum and access time to the winning SUs.

Based on the hierarchical auction framework, we first propose TERA, a Truthful auction mechanism for Efficient Resource Allocation in CCRNs. In TERA, each secondary relay will randomly separate its corresponding SUC into two subsets and charge different unit price for those two subsets. Even though TERA satisfies truthfulness, we notice that it may be unfair to charge different unit prices in TERA inasmuch as winners in those two subsets just get the identical relay node and spectrum. Therefore, to ensure the fairness among SUs in the same SUC, we further propose UERA which will charge a uniform unit price for the SUs who get the identical relay node and spectrum. UERA is not a truthful scheme indeed, but we prove that it achieves another appealing property known as approximate truthful [17] which means that each participant has no more than a small additive incentive to reply non-truthfully. Furthermore, we prove that both TERA and UERA satisfy other critical economic properties, such as individual rationality, budget balance, supply limits and computational efficiency, which are defined in Section 3.4.

By theoretical analysis, we show that TERA can achieve near-optimal revenue with high probability and UERA can achieve near-optimal expected revenue. Moreover, Our simulations verify the performance of our proposed schemes. Especially, TERA can improve the utility of PUs and relay nodes significantly up to 125 and 151% compared with a random method respectively. UERA can also improve the utility of PUs and relay nodes significantly up to 108 and 134% compared with a random method while ensure fairness among SUs.

The remainder of this paper is organized as follows. In Section 2, a brief review of related work is given. We provide some preliminaries and give the problem formulation in Section 3. Next, we propose and analyze our TERA scheme in Section 4. UERA is presented in Section 5. Simulation results are given in Section 6. Finally, we conclude our work in Section 7.

2. Related work

In this section, we briefly review related works for relay allocation and spectrum allocation in wireless networks.

2.1. Non-auction work

Relay allocation has been extensively studied in cooperative networks in the past decade. Extensive related studies concentrate on the performance of transmission capacity. The authors in [3] studied the relay node assignment problem in a network environment, where multiple source-destination pairs compete for the same pool of relay nodes in the network. The authors in [18] gave a relay assignment algorithm with interference mitigation for cooperative communication. However, in [3,18], a relay node can be assigned to at most one source node which is impractical. In contrast, the authors in [14,15] studied the problems that multiple source nodes share the same relay nodes, which are similar to our work. The other line of previous work aims at improving energy efficiency. For example, Huang et al. proposed a series of power allocation schemes in different scenarios, such as energy harvesting enabled relay networks [39] and relay-enhanced OFDM systems [40]. Nevertheless, those works cannot be applied in CCRNs because they did not consider the spectrum allocation.

Besides, numerous previous works have addressed the spectrum allocation problem in cognitive radio networks. Sun and Zhu [48] proposed an efficient distributed algorithm in multi-hop cognitive radio networks to maximize spectrum utilization. Huang et al. [42] gave a comprehensive survey on the energy-efficient resource allocation techniques in green-energy-powered cognitive radio networks. To maximize the network capacity of cognitive radio networks, Yousefvand et al. [43] presented a novel interference constraint capacity-aware spectrum allocation model. However, the character that relay and spectrum allocation is coupled makes the resource allocation in CCRN unique and challenging.

The joint allocations of spectrum and relay in CCRNs have attracted lots of attention recently. The authors in [6] studied the resource allocation in Orthogonal Frequency Division Multiplexing (OFDM)-based CR networks with cooperative relays. In [4], the authors investigated the problem of energy-efficient in cooperative cognitive radio networks by taking power control, relay assignment and channel allocation into consideration. Afterwards, they