An Auction Theory Based Algorithm for Throughput Maximizing Scheduling in Centralized Cognitive Radio Networks

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Abstract—**In this letter we propose an auction theory based algorithm for throughput maximizing scheduling in centralized cognitive radio networks (CRN). In the considered CRN scheme, a centralized base station coordinates the assignment of frequencies and time slots to cognitive users with multiple antennas. Our proposed algorithm uses first-price sealed bid auction mechanism in which frequency and time slot pairs are considered as the auctioned resources and cognitive users are the bidders. The experimental results show that our computationally efficient algorithm yields very close throughput performance to the optimization software CPLEX values.**

Index Terms—**Auction algorithm, first price sealed bid auction, resource allocation, scheduling, dynamic spectrum access, cognitive radio networks.**

I. Introduction

RADIO spectrum is a finite resource and its effective usage gains importance as the wireless devices proliferate. However, it has been observed that spectrum is sparsely utilized in some portions of the frequency band, while it is overcrowded in other portions [1]. This nonhomogeneous usage leads to the suffering of some frequency bands from service quality due to heavy load, while low utilization of the other bands decreases spectrum efficiency. In order to overcome this inefficiency, *dynamic spectrum access* (DSA) is introduced as opposed to today's fixed spectrum assignment policy. DSA can be realized by cognitive radio technology, initially proposed by [2]. Cognitive radios achieve DSA by being aware of their environment and changing their transmission and reception parameters according to the network state and user demands.

CRNs consist of primary users and secondary users. A primary user (PU) is a licensed user who has privileged rights to access the radio spectrum. A secondary user (SU), being an unlicensed user, can only access the temporarily unused licensed spectrum bands and is obliged to vacate the spectrum band it uses as soon as the primary owner of the band appears.

In this letter, we propose an auction theory based scheduling method to address the throughput optimal scheduling problem formulated in [3]. The scheduling model in [3], which is assumed to be executed by the central cognitive base station (CBS), maximizes the total throughput of the SUs in the service area while it ensures that each SU is assigned at least one time slot in any scheduling period, no collisions occur among the SUs, and none of the PUs get disturbed. The experiments show that our proposed mechanism yields results which are very close to the values obtained from the optimization software CPLEX for varying number of cognitive users and frequencies.

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In the rest of the paper, we first describe in Section II the background work and the problem formulation. In Section III we describe our auction theory based throughput maximizing scheduler and in Section IV we discuss the experimental results. Finally, we conclude our paper in Section V.

II. Background and Problem Formulation

Auction theory is the branch of game theory dealing with incomplete information, how people behave in these auction markets, and aims to find out their game theoretical properties. Auction theory mainly deals with ascending-bid (open, oral, or English), the descending-bid, the first-price sealed-bid, and the second-price sealed-bid (Vickrey) auction types in different application areas. Besides providing mathematical models of these types by examining the obtained data from previous auctions (including other combinations of these four types), it explores new auction procedures for specific applications.

In the ascending auction, the price is successively raised until one bidder remains, winning the object at the final price. Conversely, in the descending auction the auctioneer starts at a very high price, and then lowers the price continuously. In the first-price sealed-bid auction, each bidder independently submits a single bid without seeing others' bids, and the object is sold to the bidder who makes the highest bid. Different from the first-price, in the second-price sealed-bid auction, the winning bidder pays the second highest bidders' bid [4].

In addition to the usage of auction theory in real world auctions like airport time slots, railroad segments and delivery routes, some research studies on utilizing spectrum via dynamic spectrum access using auction mechanism for CRNs have been conducted in [5], [6], [7], [8], [9], [10], [11]. In [5], authors introduce a spectrum management policy that simultaneously satisfies the spectrum regulator (i.e., general public interests), the service provider (i.e., operator), licensed users, and unlicensed users. In [6], the authors discuss the problem from these four parties' point of view but they do not guarantee the quality of service of the users. In [7], spectrum sharing among a PU and multiple SUs is considered. Authors formulate the problem of sharing the spectrum as an oligopoly market competition and use a noncooperative game to which Nash equilibrium is considered to be the solution in order to obtain the spectrum allocation for SUs. In [8], the authors model the spectrum allocation in wireless networks with multiple selfish legacy spectrum holders and SUs as multi-stage dynamic games. In [9], only the interaction among SUs is considered via a non-cooperative model. It uses a power/channel allocation scheme that uses a distributed pricing strategy to improve the network's performance. In [10], the problem is formulated as a bandwidth auction in which each SU makes a bid for the amount of spectrum assigned by the PU which takes into account that the assignment does not decrease its own performance. Authors in [10] show that the auction is a non-cooperative game and again Nash equilibrium is considered as the solution of this game. In [11] authors model the problem of spectrum sharing among a few PUs and multiple SUs through second-price and Vickrey type of auctions.

In [3] a centralized CRN architecture where the CBS leads the SUs, which may have several antennas, is considered. In that model, in the first stage every SU computes the maximum number of packets that they can transmit for every frequency. Subsequently, central CBS determines with which frequency each SU will transmit in each time slot, while ensuring that the SU transmissions do not disturb any PU in the region. In the second stage, a binary integer linear programming problem (BILP) is solved. In the simulations part of [3], this BILP is solved using the optimization software CPLEX [12]; however, BILP can in general be NP-hard and a commercial optimization software may not always be available in real life situations like in the premises of the CBS operator. Furthermore, the running times of an optimization software may also be high. In this paper, we propose an auction based computationally efficient heuristic algorithm to address the BILP problem formulated in [3]. Since our optimization problem has unique constraints such as ensuring that each SU is assigned at least one time slot and each SU possibly has multiple antennas, the existing auction mechanisms in the literature fail to address these types of constraints. Therefore, our proposed heuristic algorithm uses a novel auction mechanism tailored for our optimization problem while it yields very close performance to the CPLEX results in [3], and it has low computational complexity. Note here that our proposed algorithm is designed to be implemented at the CBS; i.e., the auctioning procedures do not necessitate any additional message exchange between the SUs and the CBS in a real-life scenario since they are only conceptual steps of the algorithm.

At the end of the first stage in [3], CBS constructs a matrix called U = [U_{if}] where U_{if} is the maximum number of packets that can be transmitted by user i using frequency f. The number of packets an SU can send by using a frequency is the same for all time slots of a scheduling period. Henceforth, the following BILP is formulated in [3]:

$$max(\sum_{i=1}^{N}\sum_{f=1}^{F}\sum_{t=1}^{T}\frac{U_{if}X_{ift}}{T}) \tag{1}$$

$$s.t.$$

$$\sum_{f}\sum_{t}X_{ift} \geq 1; \forall i \epsilon \{1,2,..,N\} \tag{2}$$

$$X_{ift} + X_{i'ft} \leq 1; \forall i, i' \epsilon \{1,2,..,N\}, i \neq i', \forall f, \forall t \tag{3}$$

$$\sum_{f} X_{ift} \leq a_i; \forall i, \forall t \tag{4}$$

where N is the total number of SUs, F is the total number of frequencies, T is the total number of time slots, X_{ift} is a binary variable such that $X_{ift} = 1$ if SU i transmits with frequency f in time slot t and 0 otherwise, and a_i is the number of transceivers (antennas) of SU i. In the above formulation, (2) ensures that each SU is assigned at least one time slot, whereas (3) guarantees that at most one SU can transmit in a certain time slot and frequency pair, thereby avoiding collisions among the SUs. Since each transceiver can tune to at most one frequency at a time, (4) stands for the fact that an SU i cannot transmit at the same time using frequencies more than the number of its transceivers, a_i.

III. Proposed Scheduler

A. Auction Theory Based Scheduling Algorithm

We address the optimization problem formulated in (1) - (4) and propose a first-price sealed-bid auction based scheduling algorithm, which is an efficient heuristic approach to the problem. In our CRN model, we assume that all SUs led by the same central BS have the same number of transceivers.

In the optimization problem in (1) - (4) a frequency f and time slot t pair constitutes a resource r. Notice here that if we ignore constraint (2) and (4) in this problem, the optimal solution is achieved when each resource r is assigned to the SU i that has the maximum U_{if} value for the frequency f of this resource r. In other words, all the time slots of a frequency f are assigned to SU i where $i = arg\,max_i(U_{if})$. In the rest of this paper we use the term *"starving user"* for each SU that has not yet been assigned any time slot during any stage of the algorithm. Since the optimization problem aims to assign at least one frequency time slot resource pair (FTRP) to each SU, our auction algorithm avoids having starving users at the end of the algorithm.

Our proposed algorithm is explained through Step 1 to Step 5 below. Here, n_i denotes the number of frequencies assigned to SU i at the end of Step 1. Recall that *starving user* stands for SUs to whom no FTRP is assigned yet.

STEP 1: For each frequency, find the SU who transmits the maximum number of packets using that frequency and assign the frequency to that SU for all time slots of the scheduling period. In other words, assign frequency f to SU i where $i = arg\,max_i(U_{if})$.

STEP 2: If all SUs are assigned at least one FTRP and $n_i \leq a_i, \forall i$, return. Otherwise, each SU that is assigned more than one frequency sorts its frequencies according to their U_{if} values. If any SU i has n_i greater than a_i in any time slot, go to STEP 3, else go to STEP 4.

STEP 3: If there exists any starving user go to 3a, else go to 3b.

3a: Any SU i whose $n_i \geq a_i$ auctions all time slots of $n_i - a_i$ of its frequency bands which have the smallest U_{if} values. The FTRPs which belong to the same time slot are auctioned simultaneously. Starving users bid to the FTRP, whose corresponding U_{if} value is the greatest one among all simultaneously auctioned FTRPs. As soon as a starving user gets an FTRP, it does not participate in the subsequent auctions anymore. The auctions continue until either all of the starving users get one FTRP or no FTRP remains. At the end of the auctioning procedure if all resources are assigned and there still exists some starving users go to Step 4. Otherwise, if there still exists FTRPs that are not assigned to any SU, they are auctioned to the bidders who have available transceivers.

3b: Any SU i whose $n_i \geq a_i$ takes a_i of its frequency bands which have the largest U_{if} values. The FTRPs which belong to the remaining $n_i - a_i$ frequencies are assigned greedily to the SUs who have available transceivers.

STEP 4: Any SU i who is assigned more than one frequency auctions T time slots of $n_i - 1$ number of its frequencies which have the smallest U_{if} values until either no starving SU remains or the auctioned FTRPs run out. When all SUs have at most a single frequency, if any starving SU exists, they auction $T - 1$ time slots of their remaining frequencies.

U_{if} values of any SU i is independent from other SUs' values, and each SU knows only its own U_{if}, namely bid values. Since the bids do not affect each other, the auctions are held in a sealed bid fashion. Moreover, in order to maximize the network throughput, first-price auctions are used in the algorithm steps and an auctioned FTRP is assigned to an SU whose bid is greater than all other bids. The result of an auction related to an FTRP does not impact another auction which is held simultaneously. Hence, if we had used multi-bid auctions, some starving users might end up with receiving more than one frequency and time slot pair while some other starving users continue to starve. This situation would obligate additional number of auctions in order to guarantee that the algorithm terminates and hence increase the complexity and running time of the algorithm. Therefore, having a first price sealed bid auction renders our proposed algorithm simpler by avoiding additional operations to ensure the termination of the algorithm.

B. Computational Complexity Comparison

The worst case scenario occurs when at the end of Step 1 all of the F frequencies are assigned to one user, remaining $N-1$ users starve and the starving users always bid to the same FTRP in the simultaneous auctions. The order of the greedy assignment in Step 1 is $O(FN)$ because for each frequency f, its largest U_{if} value is found. In Step 2, the U_{if} values of F number of frequencies are sorted and the complexity of this operation is $O(Flog(F))$. We can use the term "*simultaneous auctions set*" for the auctions in which the FTRPs that belong to the same time slot are auctioned simultaneously. Since in the worst case scenario all starving SUs always bid to the same FTRP, in each simultaneous auctions set only one starving user gets an FTRP. Thus, $N-1$ number of simultaneous auctions sets must be held to assign an FTRP to each starving user. A simultaneous auctions set takes $O((N-1)log(N-1))$ time because it involves sorting the bids of $N-1$ starving SUs. Thus $(O(FN))+O(Flog(F))+(N-1)\times O((N-1)log(N-1))$, which is roughly equal to $O((FN)+N^2log(N))$, is the total time complexity of the worst case scenario. Best case scenario occurs if at the end of initial greedy assignment all SUs are assigned at least one frequency and time slot pair and (4) is not violated. In that case time complexity becomes $O(FN)$.

IV. Simulation Results

For the simulations we use the same CRN environment explained in [3], in which a CRN cell has 600 meters radius and each scheduling period consists of 10 time slots, where each time slot is 100 ms long. U_{if} values for 5000 scheduling periods in each set of simulations are obtained by taking PU velocities, SU velocities, and number of PUs into account [3]. We consider a random waypoint mobility model for SUs and PUs as in [3]. In our experiments, we set both PU and SU velocities to 13 m/s and the number of antennas $a_i = 3$, $\forall i$. We vary the number of SUs (N) between 5 and 30.

In Fig. 1, we present the resulting total throughput values for $F = 3$, $F = 18$, and $F = 30$. F_{CPLEX} denotes the number of frequencies used in the CPLEX simulations, whereas F_{AUC} denotes the number of frequencies used in our proposed auction based algorithm. We observe that our algorithm yields very close results to the CPLEX solutions in all cases.

In addition, the simulation results show that the algorithm tends to exhibit its worst case behavior when U_{if} values of the SUs are close to each other. In this case, bidders generally bid

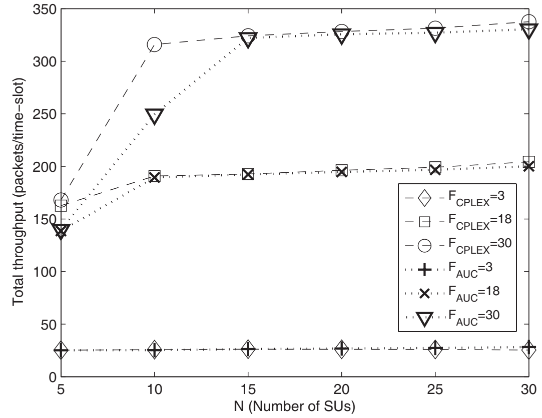

Fig. 1. Comparison of proposed algorithm results with the CPLEX results in [3].

to the same auctioned frequencies and thus the total number of auction procedures increases. Nevertheless, since even the worst case computational complexity is $O((FN)+N^2log(N))$ (proved in Section III-B), our algorithm has a reasonable running time even when the situation of having akin U_{if} values occurs.

V. Conclusion

In this letter we propose an auction theory based scheduler for centralized cognitive radio networks. Our method is based on a novel auction policy which uses first-price sealed bid auctions. The algorithm has $O((FN)+N^2log(N))$ complexity in the worst case scenario and $O(FN)$ when the best case holds, where N is the total number of secondary users and F is the total number of frequencies in the cognitive radio cell. Our simulations with varying number of secondary users show that the results of our proposed algorithm are very close to the values obtained by the CPLEX.

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