Dynamic Spectrum Access and Power Allocation for Cooperative Cognitive Radio Networks

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***Abstract*—In the existing cooperative cognitive radio, primary users are generally assumed to be more than capable of supporting their target throughput, thereby the rate enhancement or the cooperation from secondary users actually has less attraction to primary users. Instead, they might be more interested in the benefits in other format. This paper presents a new cooperative cognitive radio framework, where primary users are willing to cooperatively relay data for secondary users with their under-utilized resource to earn the revenue. An auction model with multiple auctioneers, multiple bidders and hybrid divisible/indivisible commodities is proposed to solve channel bands and cooperative transmit power competitions among secondary users. For maximizing the utility, secondary users can select receiving primary user's assistance (i.e., work in cooperative transmission mode) and purchase both spectrum and power from the primary user, or select direct transmission mode and just buy spectrum from the primary user. Then, the convergence of the proposed auction scheme to a Walrasian equilibrium is mathematically proved. Finally, the performance of the proposed scheme is verified by the simulation results.**

***Index Terms*—Auction, cooperative cognitive radio, dynamic spectrum access, power allocation, Walrasian equilibrium.**

I. INTRODUCTION

A report from the Federal Communications Commission [1] reveals a fact that the emerging "spectrum shortage" comes from the inefficient spectrum usage rather than the real spectrum scarcity. Cognitive radio (CR) or dynamic spectrum access (DSA) [2]–[6], is proposed as a promising technique to enable spectrum sharing. It allows secondary users to dynamically access the licensed spectrum belonging to primary users without causing a harmful interference. Recently, incorporation of cooperation concept [7], [8] into CR networks has become a new cognitive radio paradigm. It employs cooperative relay to assist the transmission and improve the spectrum efficiency.

Existing works on cooperation in CR networks are classified into two categories: i) cooperation among secondary users; ii) cooperation between primary and secondary users. In the first category, a secondary user acts as a relay and assists transmissions of other secondary users [9], [10]. Generally, the solutions for traditional cooperative communications are valid for cooperation among secondary users. The only difference is that the DSA of secondary users must be considered in the latter. In the second category, the property rights [11] of primary users in spectrum are recognized. Therefore, primary users have the rights to sell or lease the owned spectrum to secondary users.

The cooperation between primary and secondary users in the literature [12]–[21] concentrated on the scenario where the resources owned by primary users are more than capable of supporting their target quality of service (QoS) [22], thereby they can lease a certain fraction of the channel access time which is idle temporarily to secondary users, and in return secondary users help relaying for primary transmission. Since primary users can achieve the target throughput by itself, the rate enhancement or the cooperation from secondary users actually has less attraction. Instead, they might be more interested in the benefits in other format (e.g. revenue).

This motivates us to consider a new cooperation way, i.e., primary users cooperatively relay data for secondary users on the premise that this would not do harm to the performance of their own transmissions. In exchange, secondary users pay to primary users for the cooperative transmit power as well as the spectrum being used in cooperation. Therefore, primary users earn the revenue by selling the under-utilized resource and secondary users increase the traffic rates by exploiting cooperative diversity, thus leading to a win-win situation.

In this new cooperative transmission, secondary users require to compete for channel bands and cooperative transmit power of primary users. In this paper, we consider an auction-based spectrum access and power allocation scheme. Primary users, i.e. auctioneers, sell a portion of the channel access time and cooperative transmit power to secondary users for economic return; Secondary users, i.e. bidders, purchase channel and power from primary users for utility maximization. The prices announced by primary users for the channel and power are determined by the ascending clock auction algorithm.

The main contributions of this article are summarized as follows:

1) We present a new cooperative cognitive radio framework. Specifically, we divide each time slot of a primary transmitter into two portions respectively for primary and secondary users. Primary users finish their own transmissions in primary portion, and then provide relaying service

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for secondary users. In secondary portion, secondary users may select receiving primary user's help (i.e. cooperative transmission) or direct transmission for maximizing the utility.

2) We formulate the spectrum access and power allocation problem as an auction model where multi-auctioneer, multi-bidder and hybrid divisible/indivisible commodities are considered, and propose a resource allocation scheme based on the ascending clock auction algorithm. Each bidder (secondary user) can choose one auctioneer (primary user) and then purchase either one commodity (channel) or two commodities (channel and power) from it. As the channel and power are two heterogeneous commodities, of which the channel is indivisible and can be assigned either totally or nothing, while the power is divisible and can be offered at any quantity, their different properties are particularly considered in the auction scheme.
3) We investigate the outcome of the proposed auction scheme, and mathematically prove the convergence (i.e., the convergence to a Walrasian equilibrium) of the proposed auction where divisible and indivisible commodities are co-existed. Also, we verify that the proposed auction is beneficial to both primary and secondary users by numerical results.

The remainder of this paper is organized as follows: Section II presents the related work on cooperative CR as well as auction-based spectrum and power allocation. Section III introduces the system model and the basic assumptions. Section IV describes a dynamic spectrum access and power auction mechanism for the proposed cooperative CR system. In Section V, the convergence performance of the proposed auction game is theoretically analyzed. Numerical results are presented and discussed in Section VI. Finally, Section VII concludes the paper.

II. Related Work

The concept of cooperative cognitive radio has only been proposed recently [12]–[21]. Simeone *et al.* in [12] proposed a cooperation-based spectrum leasing scheme, where a primary user leases the owned spectrum to a subset of secondary users for a fraction of time in exchange for cooperation from secondary users. Zhang *et al.* in [13] proposed a cooperative cognitive radio network framework, in which some secondary users are selected by primary users as cooperative relays and in return, they obtain more spectrum access opportunities. Huang *et al.* in [14] assumed that the primary user does not have incomplete information of the secondary users energy cost and modeled cooperative spectrum sharing as a dynamic Bayesian game. An asymmetric cooperative communications architecture was proposed in [15], where the secondary user relays the primary data with its own transmit power for the usage of the spectrum, while the primary user transmits only its own data. Similar works can also be found in [16]–[21]. Unlike the existing works, we study a new cooperative cognitive radio architecture, where primary users act as cooperative relays and assist secondary transmission for profit.

Auction theory [23] is viewed as a simple and powerful tool for distributed resource allocation in interactive multiuser systems. Auction-based channel and power allocation have been extensively studied in the literature [24]–[29]. For instance, the SNR auction and the power auction schemes were proposed in [24] to coordinate the relay power allocation among users on the basis of amplify-and-forward relaying protocol. The authors in [25] proposed a two-level buyer/seller game for cooperative transmit power allocation, in which the interests of source nodes and relay nodes are jointly considered. The authors in [27] formulated the channel allocation problem in CR networks as an auction game and discussed three kinds of auction algorithms. A multi-auctioneer progressive auction algorithm was proposed in [29], where multiple secondary users bid for the channels from multiple primary users.

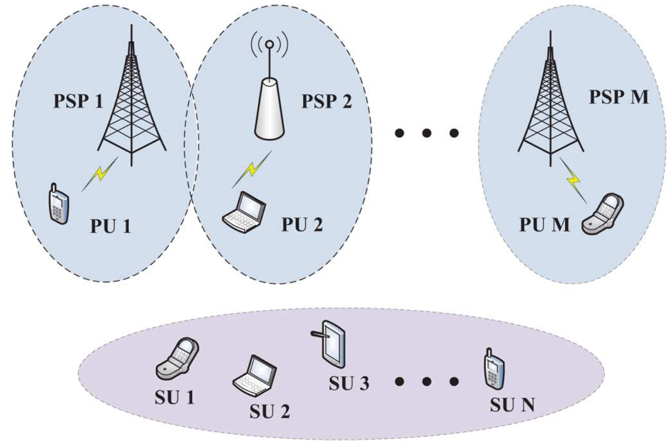

Fig. 1. Architecture of the proposed CR system.

The existing spectrum or power auction models are characterized by single auctioneer multiple bidders for single commodity as in [27], or multiple auctioneers multiple bidders for single commodity, for example, for power auction in [26] and for spectrum auction in [29]. In this paper, we consider a joint spectrum access and power allocation problem and creatively model an auction game with multi-auctioneer, multi-bidder and multi-commodity.

III. System Model and Notations

Consider a cognitive radio system consisting of M primary service providers (PSPs), M primary users (PUs), and N secondary users (SUs). Assume that the channels owned by the same PSP are identical, i.e., they have the same bandwidth, carrier frequency, etc, while the channels for different PSPs may be different due to the heterogeneities of the PSPs. For example, as shown in Fig. 1, PSP 1 may provide cellular call service on the frequency of 900 MHz, and PSP 2 may offer wireless LAN access on the frequency of 5 GHz. For each PSP j, there is a PU j, equipped with a primary transmitter (PT) and a primary receiver (PR), and K_j non-overlapping narrowband channels. Note that the scenario that each PSP j serves K_j PUs with each PU owning only one channel can be analyzed straightforwardly in the same fashion. In the secondary network, each secondary user (SU) i is equipped with a secondary transmitter (ST) and a secondary receiver (SR). The PTs act as relays to assist STs' transmissions by the decode-and-forward (DF) relaying protocol. Also, assume that each channel of the PT can be accessed by only one ST at the same time, and the channel occupancy by the STs is maintained by each PT itself. To simplify the analysis, we consider the scenario where the total number of the licensed channels in the system equals to the number of STs, i.e., $N = \sum_{j=1}^{M} K_j$, such that each ST can access one channel.

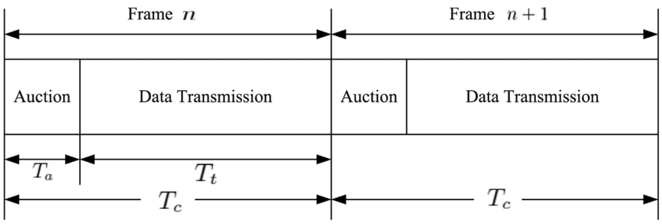

Fig. 2. Frame structure of the proposed CR system.

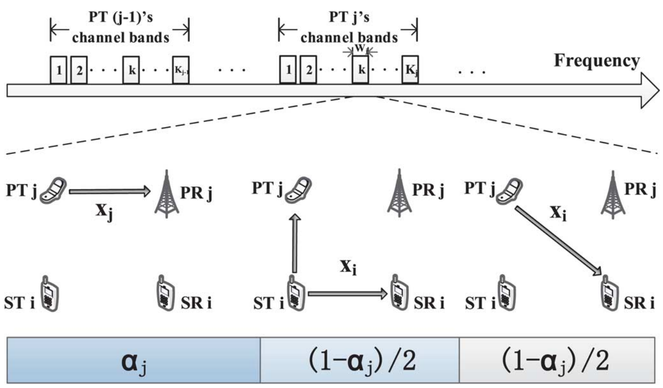

Fig. 3. Cooperative transmission in data transmission slot.

The frame structure of the proposed CR system is shown in Fig. 2. T_c represents the duration of one frame that consists of one auction slot T_a and one data transmission slot T_t. In the auction slot, the ST, which intends to send data to its SR, selects a desired PT (e.g. PT j) and joins the channel and power auction organized by that PT. At each channel of PT j, the data transmission slot is divided into two portions, α_j and $1-\alpha_j$ $(0<\alpha_j\leq 1)$. The portion α_j of the slot is used for primary traffic (called primary portion) and the portion $1-\alpha_j$ is for secondary traffic (called secondary portion), as shown in Fig. 3.

In secondary portion, each ST i has two transmission modes: direct transmission and cooperative transmission. If ST i selects direct transmission mode, it sends the data to its receiver directly over the entire secondary portion. In this case, ST i only uses PT j's channel. If ST i works in cooperative transmission mode, the secondary portion is further equally decomposed into two sub-slots. In the first sub-slot, ST i sends the data to SR i. Meanwhile, the data are overheard by PT j; In the second sub-slot, PT j forwards the overheard data to SR i. In this case, ST i requires to purchase the power as well as the channel from PT j.

We now give out some operating assumptions of our system model: 1) Assume that the channels change slowly and the channel gain is stable within each frame. This assumption is widely used in the literature [24]–[26] for optimal resource allocation over wireless fading channels. It simplifies our analysis, but our work can be considered as a baseline analysis for more complicated scenarios. 2) Assume that the channel state information (CSI) can be accurately measured at each receiver. Note that for slow-fading channel, i.e., the channel coherence time is large enough, the CSI can be accurately estimated within a sufficiently long period of observation.

In Primary Portion: At each channel of PU j, PT j transmits its signal to its destination PR j with power P_j. Assume that the total transmit power P_{U_j} of PT j is equally used at each channel at this portion, i.e., we have $P_j = P_{U_j}/K_j$. The signal received at PR j is given by

$$Y_{PT_j}^{PR_j} = \sqrt{P_j} G_{PT_j}^{PR_j} X_j + n_{PR_j}, \tag{1}$$

where Y_A^B represents the signal received at B from A, X_j is the information symbol transmitted by PT j with $E[|X_j|^2] = 1$, and $n_{\{\cdot\}}$ is the additive white Gaussian noise (AWGN) with variance σ^2. G_A^B denotes the channel gains from A to B, which is also the channel gains from B to A. The amplitude $|G_A^B|^2$ is exponentially distributed, with rate parameter $\lambda_A^B = (d_A^B)^\alpha$, where d_A^B denotes the distance between A and B, and α is the path-loss exponent.

Thus, the achievable rate from PT j to PR j over one channel is

$$R_j = \alpha_j \cdot W_j \log_2\left(1 + \frac{P_j \left|G_{PT_j}^{PR_j}\right|^2}{\sigma^2}\right), \tag{2}$$

where W_j is the bandwidth of the channel.

In Secondary Portion: For each ST i, we consider two cases, cooperative transmission and direct transmission.

a) Cooperative transmission:

In the First Sub-Slot: ST i transmits its signal with power P_i. The signals received by SR i and PT j are respectively

$$Y_{ST_i}^{SR_i} = \sqrt{P_i} G_{ST_i}^{SR_i} X_i + n_{SR_i}, \tag{3}$$
$$Y_{ST_i}^{PT_j} = \sqrt{P_i} G_{ST_i}^{PT_j} X_i + n_{PT_j}, \tag{4}$$

where X_i is the signal transmitted by ST i in this phase with $E[|X_i|^2] = 1$.

Thus, the signal-to-noise ratio (SNR) of X_i at SR i and PT j in the first sub-slot are $\frac{P_i|G_{ST_i}^{SR_i}|^2}{\sigma^2}$ and $\frac{P_i|G_{ST_i}^{PT_j}|^2}{\sigma^2}$, respectively.

In the Second Sub-Slot: PT j decodes X_i from $Y_{ST_i}^{PT_j}$ and forwards it to SR i. Then the signal received at SR i is

$$Y_{PT_j}^{SR_i} = \sqrt{P_{i,j}} G_{PT_j}^{SR_i} X_i + n'_{SR_i}, \tag{5}$$

where $P_{i,j}$ is PT j's cooperative transmit power for ST i.

Then, the SNR at SR i in the second sub-slot is $\frac{P_{i,j}|G_{PT_j}^{SR_i}|^2}{\sigma^2}$.

Therefore, the achievable rate from ST i to SR i in cooperative transmission is

$$R_{i,j}^{\mathrm{C}} = \frac{1-\alpha_j}{2} \min\left\{ W_j \log_2\left(1 + \frac{P_i \left|G_{ST_i}^{PT_j}\right|^2}{\sigma^2}\right), \right.$$
$$\left. W_j \log_2\left(1 + \frac{P_{i,j}\left|G_{PT_j}^{SR_i}\right|^2}{\sigma^2} + \frac{P_i\left|G_{ST_i}^{SR_i}\right|^2}{\sigma^2}\right)\right\}. \tag{6}$$

When the ST selects cooperative transmission, the PT would send an acknowledge (ACK/NACK) to the ST, notifying whether the ST's signal sent in the first sub-slot is successfully decoded or not. If the ST receives an ACK, it keeps silence in the second sub-slot; If it receives a NACK, it continues direct transmission in the second sub-slot.

b) Direct transmission: When working in direct transmission, ST i sends its data directly to SR i throughout the entire secondary portion. Therefore, the achievable rate from ST i to SR i in direct transmission is

$$R_{i,j}^{\mathrm{D}} = (1-\alpha_j) W_j \log_2 \left(1 + \frac{P_i \left| G_{ST_i}^{SR_i} \right|^2}{\sigma^2} \right). \quad (7)$$

IV. Joint Spectrum and Power Auction

In this section, we first introduce the utility function for secondary users to depict their satisfactions in the auction, then propose a joint spectrum access and power allocation scheme based on an auction game with multiple auctioneers, multiple bidders, and hybrid divisible/indivisible commodities.

A. PU's QoS Guarantee

In this work, we consider the scenario where the resources (spectrum and power) owned by primary users are more than enough to support their target transmission rates. Therefore, primary users are willing to use a certain part of the resource to help secondary users for profit, as long as the resource remained for primary users are sufficient to maintain the required QoS.

Let $R_{j,\mathrm{req}}$ represent the minimum rate required for PU j, then the primary portion α_j is determined by

$$K_j R_j = R_{j,\mathrm{req}} \Longrightarrow \alpha_j = \frac{R_{j,\mathrm{req}}}{K_j W_j \log_2 \left(1 + \frac{P_j \left| G_{PT_j}^{PR_j} \right|^2}{\sigma^2} \right)}. \quad (8)$$

Each PU $j \in \{1, \ldots, M\}$, sells two heterogeneous commodities, i.e. channel and cooperative power, among N SUs. The supply of PU j can be denoted by a vector $\mathbf{S_j} = (K_j, P_{U_j})$, which consists of the number of the licensed channels and the available cooperative power PU j has. The supply of the entire system is thereby denoted by $\mathbf{S} = (\mathbf{S_1}, \ldots, \mathbf{S_M})$. Let λ_j^1 and λ_j^2 be the prices of a channel and a power unit PU j asks for. The price vector of PU j then is denoted by $\boldsymbol{\lambda_j} = (\lambda_j^1, \lambda_j^2)$. Note that the channels owned by the same PU are assumed to be identical, i.e., they have the same bandwidth, carrier frequency, modulating scheme, etc., thus they sell at the same price.

B. SU's Utility Function

When joining the auction organized by primary users, each SU i wishes to maximize its transmission rate with minimum cost. To this end, SU i needs to determine: 1) Whether is it beneficial to use cooperative transmission or direct transmission? 2) How to select a PU as the cooperative relay and how much power should it request from that PU? 3) Or if it selects direct transmission, which PU's channel should be chosen to access? Formally, we formulate the strategies for these problems as the bids of SU i:

$$\mathbf{Q_i} = (\mathbf{Q_{i,1}}, \ldots, \mathbf{Q_{i,j}}, \ldots, \mathbf{Q_{i,M}})^T, \quad (9)$$

where $\mathbf{Q_{i,j}} = (C_{i,j}, P_{i,j}), \forall i \in \{1, \ldots, N\}$, $\forall j \in \{1, \ldots, M\}$, is a resource demand vector. $P_{i,j} \geq 0$ represents the required cooperative power of SU i from PU j. $C_{i,j} \in \{0,1\}$ specifies that whether SU i is willing to buy a channel from PU j. If it is, $C_{i,j} = 1$; Otherwise $C_{i,j} = 0$. If $C_{i,j} = 1$ and $P_{i,j} > 0$, it denotes that SU i employs cooperative transmission and chooses PU j as the relay. If $C_{i,j} = 1$ but $P_{i,j} = 0$, it tells that SU i selects direct transmission and wishes to use PU j's channel.

It is worth mentioning that the channel and the power are two different types of commodities, of which the channel is indivisible and the power is divisible. Therefore, the channel is available in a supply of one and can be assigned either totally or nothing; The power can be offered at any quantity of $P_{i,j}$, subject to the constraint that $0 \leq \sum_{i=1}^N P_{i,j} \leq P_{U_j}$. Furthermore, the channel can be sold independently at each PU, while the power must be offered together with the channel to realize cooperative transmission for the SU. It implies that the SU requires to buy the channel and the cooperative power from the same PU. If SU i does not buy the channel from PU j, i.e., $C_{i,j} = 0$, it is not allowed to purchase the power from that PU, so it has $P_{i,j} = 0$. Also, as SU i each time can access only one channel, it satisfies $\sum_{j=1}^M C_{i,j} = 1, \forall i \in \{1, \ldots, N\}$. Correspondingly, the power demand vector $\mathbf{P_i} = (P_{i,1}, P_{i,2}, \ldots, P_{i,M})$ of each SU i is a M-dimensional vector with at most one non-zero element.

To depict a SU's satisfaction with the received channel and power from PU j, we define a utility of SU i achieved from PU j's cooperation as:

$$U_{i,j}^{\mathrm{C}}(\mathbf{Q_{i,j}}, \boldsymbol{\lambda_j}) = g R_{i,j}^{\mathrm{C}}(P_{i,j}) - \lambda_j^1 C_{i,j} - \lambda_j^2 P_{i,j}, \quad (10)$$

where g is a positive constant providing conversion of units. The first term in the right side of the equation is SU i's gain (achievable rate) achieved in cooperation from PU j, and the second and the third term are the payment to PU j.

Of all the possible utilities in cooperative transmission, we define the maximum as the cooperative utility of SU i. That is

$$U_i^{\mathrm{C}}(\mathbf{Q_i}, \boldsymbol{\lambda}) = \max_{j \in \{1, \ldots, M\}} U_{i,j}^{\mathrm{C}}(\mathbf{Q_{i,j}}, \boldsymbol{\lambda_j}). \quad (11)$$

Similarly, the utility of SU i from PU j in direct transmission and the direct utility of SU i are respectively

$$U_{i,j}^{\mathrm{D}}(\mathbf{Q_{i,j}}, \boldsymbol{\lambda_j}) = g R_{i,j}^{\mathrm{D}}(C_{i,j}) - \lambda_j^1 C_{i,j}, \quad (12)$$

$$U_i^{\mathrm{D}}(\mathbf{Q_i}, \boldsymbol{\lambda}) = \max_{j \in \{1, \ldots, M\}} U_{i,j}^{\mathrm{D}}(\mathbf{Q_{i,j}}, \boldsymbol{\lambda_j}). \quad (13)$$

Finally, we define the utility of SU i as:

$$U_i(\mathbf{Q_i}, \boldsymbol{\lambda}) = \max \left\{ U_i^{\mathrm{C}}(\mathbf{Q_i}, \boldsymbol{\lambda}), U_i^{\mathrm{D}}(\mathbf{Q_i}, \boldsymbol{\lambda}) \right\}. \quad (14)$$

When SU i selects cooperative transmission and purchases the channel and power from PU j, i.e., it has $C_{i,j} = 1, C_{i,k} = 0$ for any $k \neq j$, $P_{i,j} > 0$, and $P_{i,k} = 0$ for any $k \neq j$, the optimal power demand of SU i from PU j, denoted as $P_{i,j}^*(\alpha_j, \lambda_j^2)$, can be achieved by solving the following utility maximization problem:

$$\begin{aligned} \max_{P_{i,j}} \quad & U_{i,j}^{\mathrm{C}}(\mathbf{Q_{i,j}}, \boldsymbol{\lambda_j}) = g R_{i,j}^{\mathrm{C}}(P_{i,j}) - \lambda_j^1 - \lambda_j^2 P_{i,j} \\ \text{s.t.} \quad & 0 \leq P_{i,j} \leq P_{U_j}. \end{aligned} \quad (15)$$

C. Ascending Clock Auction Mechanism

In order to efficiently allocate the channels and cooperative power of M PUs among N SUs, we model an auction game with multiple auctioneers, multiple bidders, and hybrid divisible/indivisible commodities. Each PU j, i.e. the auctioneer, iteratively announces the price vector $\boldsymbol{\lambda_j}$ of its two commodities. Each SU i, i.e. the bidder, responds to each PU j by submitting its demand $\mathbf{Q_{i,j}}$, reporting the quantities of the channel and power it wishes to purchase from PU j at these prices. PU j then calculates the *cumulative clinch* and credits the channel and power to the SUs at the current prices by the ascending clock auction algorithm [30]. Thereafter, PU j adjusts the prices according to the relationship between the total demand and the total supply. This process repeats until the prices converge at which the total demand is less than or equal to the total supply. During this process, several important operations including transmission mode selection, resource crediting, and payment calculation are involved.

1) Transmission Mode Selection: The transmission mode selection occurs on each SU before each auction clock, by which the SU determines its transmission mode in the upcoming clock, and from what PU it buys a channel and how much power it requests from that PU. For example, at the very beginning of the auction (i.e. at the time $\tau = 0$), each PU j makes an initialization, and announces the portion division α_j and the initial prices in a form of $\boldsymbol{\lambda_j}(0) = (\lambda_j^1(0), \lambda_j^2(0))$ to all the SUs. Based on these information, SU i determines its transmission mode and the bids to all the PUs.

To do that, SU i sets $C_{i,j} = 1,\ \forall j \in \{1, \ldots, M\}$, and finds out the direct utility $U_i^{\mathrm{D}}(\mathbf{Q_i}, \boldsymbol{\lambda})$ according to (13). Then, it separately solves M utility maximization problems defined in (15), and determines the cooperative utility $U_i^{\mathrm{C}}(\mathbf{Q_i}, \boldsymbol{\lambda})$. Thereafter, SU i selects the transmission mode by comparing the value of $U_i^{\mathrm{D}}(\mathbf{Q}, \boldsymbol{\lambda})$ and $U_i^{\mathrm{C}}(\mathbf{Q}, \boldsymbol{\lambda})$. If $U_i^{\mathrm{C}}(\mathbf{Q}, \boldsymbol{\lambda}) \geq U_i^{\mathrm{D}}(\mathbf{Q}, \boldsymbol{\lambda})$, SU i uses cooperative transmission and places the bids to the PU (e.g. PU j) that incurs the cooperative utility $U_i^{\mathrm{C}}(\mathbf{Q_i}, \boldsymbol{\lambda})$ as $C_{i,j}(\lambda_j^1(0)) = 1$, and $P_{i,j}(\lambda_j^2(0)) = P_{i,j}^*(\alpha_j, \lambda_j^2(0))$. For any other PU $k \neq j$, it sets the bids to $C_{i,k}(\lambda_k^1(0)) = 0$ and $P_{i,k}(\lambda_k^2(0)) = 0$. If $U_i^{\mathrm{C}}(\mathbf{Q}, \boldsymbol{\lambda}) < U_i^{\mathrm{D}}(\mathbf{Q}, \boldsymbol{\lambda})$, it selects direct transmission and sets the bids to the target PU (e.g. PU j') as $C_{i,j'}(\lambda_{j'}^1(0)) = 1$ and $P_{i,j'}(\lambda_{j'}^2(0)) = 0$. For any other PU $k \neq j'$, it has $C_{i,k}(\lambda_k^1(0)) = 0$ and $P_{i,k}(\lambda_k^2(0)) = 0$.

In order to guarantee a certain amount of the revenue even when the resource competition is very weak, the PU can set up a reserve price. It refers to the lowest price vector at which the PU is willing to sell the channel and power to the SUs. For the ascending clock auction, the PU can set its reserve price as its initial price. such that its channel and power can always be sold out at the price no less than the reserve price.

2) Resource Crediting: At each auction clock $\tau = 0, 1, \ldots$, PU j collects N SUs' bids, and computes the total required channels and power of these SUs. Let $C_j^{\mathrm{tal}}(\lambda_j^1(\tau)) = \sum_{i=1}^N C_{i,j}(\lambda_j^1(\tau))$ and $P_j^{\mathrm{tal}}(\lambda_j^2(\tau)) = \sum_{i=1}^N P_{i,j}(\lambda_j^2(\tau))$ represent the total channel and power demand at PU j at clock τ, respectively. Further, let $E_j^1(\lambda_j^1(\tau)) = C_j^{\mathrm{tal}}(\lambda_j^1(\tau)) - K_j$ and $E_j^2(\lambda_j^2(\tau)) = P_j^{\mathrm{tal}}(\lambda_j^2(\tau)) - P_{U_j}$ represent the excess channel and power demand at PU j, respectively. Then, PU j adjusts its price vector according to the excess demand.

Case 1: $E_j^1(\lambda_j^1(\tau)) > 0$ and $E_j^2(\lambda_j^2(\tau)) > 0$. It tells that the total demand for the power as well as for the channel exceeds the supply. Due to the indivisibility, K_j channels cannot be divided and fairly allocated among more than K_j competitors. Therefore, none of the channels would be credited to any competitor. As the power must be sold with the channel, the power would not be credited to any competitor, either. Hence, we have

$$\hat{C_{i,j}}\left(\lambda_j^1(\tau)\right) = 0,\ \hat{P_{i,j}}\left(\lambda_j^2(\tau)\right) = 0,\ \forall i \in \{1, 2, \ldots, N\}, \tag{16}$$

where $\hat{C_{i,j}}(\lambda_j^1(\tau))$ and $\hat{P_{i,j}}(\lambda_j^2(\tau))$ are the cumulative clinch, which are the amounts of the channel and power that are credited to SU i at the price $\boldsymbol{\lambda_j}(\tau)$.

After finding out the cumulative clinch, PU j updates its price vector with $\lambda_j^1(\tau+1) = \lambda_j^1(\tau) + \mu_j^1$ and $\lambda_j^2(\tau+1) = \lambda_j^2(\tau) + \mu_j^2$, where $\mu_j^1 > 0$ and $\mu_j^2 > 0$ are step sizes. Thereafter, PU j announces this new price vector to all the SUs. Each SU then re-selects the transmission mode based on the new announced price and starts a new bidding round.

Case 2: $E_j^1(\lambda_j^1(\tau)) > 0$ and $E_j^2(\lambda_j^2(\tau)) \leq 0$. In this case, there are more than K_j SUs competing for K_j channels at PU j, whose total power demand is less than PU j's supply. Similar to Case 1, neither the channel nor the power would be credited to any competitor. Therefore, the cumulative clinch of the channel and power to the SUs are also determined by (16). Finally, the price of the channel is updated by $\lambda_j^1(\tau + 1) = \lambda_j^1(\tau) + \mu_j^1$, while the price of per unit power remains unchanged as $\lambda_j^2(\tau + 1) = \lambda_j^2(\tau)$ for the sake that the total power demand does not exceed the supply.

Case 3: $E_j^1(\lambda_j^1(\tau)) \leq 0$ and $E_j^2(\lambda_j^2(\tau)) > 0$. In this case, the competition for the power is fierce, and that for the channel is weak. As the supply of the channel is sufficient, the channels can be directly credited to all the competitors who bid for them. Moreover, the power can be credited to each competitor in terms of their opponents' demands. Thus, for each SU i with $C_{i,j}(\lambda_j^1(\tau)) = 1$, we have

$$\begin{aligned} &\hat{C_{i,j}}\left(\lambda_j^1(\tau)\right) = 1, \\ &\hat{P_{i,j}}\left(\lambda_j^2(\tau)\right) = \max\left(0, P_{U_j} - \sum_{k=1, k\neq i}^{N} P_{k,j}\left(\lambda_j^2(\tau)\right)\right). \end{aligned} \tag{17}$$

For each SU i with $C_{i,j}(\lambda_j^1(\tau)) = 0$, we have

$$\hat{C_{i,j}}\left(\lambda_j^1(\tau)\right) = 0,\ \hat{P_{i,j}}\left(\lambda_j^2(\tau)\right) = 0. \tag{18}$$

Thereafter, PU j updates the price vector with $\lambda_j^1(\tau + 1) = \lambda_j^1(\tau)$ and $\lambda_j^2(\tau + 1) = \lambda_j^2(\tau) + \mu_j^2$.

Case 4: $E_j^1(\lambda_j^1(\tau)) \leq 0$ and $E_j^2(\lambda_j^2(\tau)) \leq 0$. It shows that the supplies of both the channel and power are sufficient for all the competitors. Therefore, each competitor would be credited according to its demand, i.e.,

$$\hat{C_{i,j}}\left(\lambda_j^1(\tau)\right) = C_{i,j}\left(\lambda_j^1(\tau)\right),\ \hat{P_{i,j}}\left(\lambda_j^2(\tau)\right) = P_{i,j}\left(\lambda_j^2(\tau)\right). \tag{19}$$

The price vector is then kept static with $\lambda_j^1(\tau+1) = \lambda_j^1(\tau)$ and $\lambda_j^2(\tau + 1) = \lambda_j^2(\tau)$.

Additionally, the demand $\mathbf{Q_{i,j}}(\boldsymbol{\lambda_j}(\tau))$ of SU i from PU j is a function of PU j's announced price $\boldsymbol{\lambda_j}(\tau)$. If PU j's price is too high at τ, SU i which chose PU j at $\tau - 1$ might give up it and turn to another PU at τ, then all the channel and power clinched to SU i before τ at PU j become unclinched. Thus, all the credits SU i received before from PU j should be cleared. So, in the above four cases, for SU i with $C_{i,j}(\lambda_j^1(\tau)) = 0$ and $C_{i,j}(\lambda_j^1(\tau - 1)) = 1$, we have

$$\hat{C_{i,j}}\left(\lambda_j^1(\tau')\right) = 0,\ \hat{P_{i,j}}\left(\lambda_j^2(\tau')\right) = 0,\ \forall \tau' \in \{0, 1, \ldots, \tau - 1\}. \tag{20}$$

3) Payment Calculation: If the supply meets the demand for each PU at $\tau = T$, i.e., $E_j^1(\lambda_j^1(T)) = 0$ and $E_j^2(\lambda_j^2(T)) \leq 0$, $\forall j \in \{1, \ldots, M\}$, the auction ends with an equilibrium price $\boldsymbol{\lambda}^* =$

$\boldsymbol{\lambda}(T)$. Consider that the power supply P_{U_j} of PU j might not be fully covered at $\lambda_j^2(T)$ (i.e. $E_j^2(\lambda_j^2(T) < 0)$, which occurs when the aggregate power demand of the SUs that select PU j as the cooperative relay is less than PU j's supply. For each SU i with $\hat{P_{i,j}}(\lambda_j^2(T)) \neq 0$, we re-calculate its cumulative clinch by [30]:

$$\begin{aligned}\hat{P_{i,j}}\left(\lambda_j^2(T)\right) = &P_{i,j}\left(\lambda_j^2(T)\right)\\ &+\frac{P_{i,j}\left(\lambda_j^2(T-1)\right)-P_{i,j}\left(\lambda_j^2(T)\right)}{\sum\limits_{i=1}^{N}P_{i,j}\left(\lambda_j^2(T-1)\right)-\sum\limits_{i=1}^{N}P_{i,j}\left(\lambda_j^2(T)\right)}\\ &\times\left[P_{U_j}-\sum_{i=1}^{N}P_{i,j}\left(\lambda_j^2(T)\right)\right]. \qquad (21)\end{aligned}$$

Such that the power supply is exactly equal to the demand, and we have $E_j^2(\lambda_j^2(T)) = 0$.

Thus, the quantities of the channel and power that are assigned to SU i are given by

$$\begin{aligned}C_{i,j}^* = \hat{C_{i,j}}\left(\lambda_j^1(T)\right),\ P_{i,j}^* = \hat{P_{i,j}}\left(\lambda_j^2(T)\right),\\ \forall i \in \{0,1,\ldots,N\},\ \forall j \in \{0,1,\ldots,M\}. \qquad (22)\end{aligned}$$

Correspondingly, the payment for the channel from SU i to PU j is

$$\begin{aligned}V_{i,j}^1 = &\lambda_j^1(0)\hat{C_{i,j}}\left(\lambda_j^1(0)\right)\\ &+\sum_{\tau=1}^{T}\lambda_j^1(\tau)\left(\hat{C_{i,j}}\left(\lambda_j^1(\tau)\right)-\hat{C_{i,j}}\left(\lambda_j^1(\tau-1)\right)\right), \qquad (23)\end{aligned}$$

and the payment for the power from SU i to PU j is

$$\begin{aligned}V_{i,j}^2 = &\lambda_j^2(0)\hat{P_{i,j}}\left(\lambda_j^2(0)\right)\\ &+\sum_{\tau=1}^{T}\lambda_j^2(\tau)\left(\hat{P_{i,j}}\left(\lambda_j^2(\tau)\right)-\hat{P_{i,j}}\left(\lambda_j^2(\tau-1)\right)\right). \qquad (24)\end{aligned}$$

If all the SUs that select PU j's channel choose direct transmission when the auction concludes, none of these SUs would need the power from PU j. In fact, it can be equivalently viewed as a special case in which PU j only takes out the channels for sale and leaves the power for its own use. Therefore, all the power assignments and power payments with respect to PU j become zero, which can also be achieved by (22) and (24). For an extreme case when all the SUs in the system select direct transmission, the proposed multi-auctioneer, multi-bidder, multi-commodity auction degrades to an auction with multiple auctioneers and multiple bidders for single commodity. A complete channel and power auction algorithm is shown in Algorithm 1.

Algorithm 1: The Proposed Channel and Power Auction Algorithm

Initialization

Sets clock index $\tau = 0$;

Each PU $j \in \{1,\ldots,M\}$ announces its portion division α_j and initial price vector $\boldsymbol{\lambda_j}(0) = (\lambda_j^1(0), \lambda_j^2(0))$ to all the SUs.

Iteration Step ($\tau = 0,1,2,\ldots$)

At a SU $i \in \{1,\ldots,N\}$:

Input: Receives α_j and $\boldsymbol{\lambda_j}(\tau) = (\lambda_j^1(\tau), \lambda_j^2(\tau))$ from each PU $j \in \{1,\ldots,M\}$.

Chooses transmission mode by comparing $U_i^{\mathrm{D}}(\mathbf{Q},\boldsymbol{\lambda})$ and $U_i^{\mathrm{C}}(\mathbf{Q},\boldsymbol{\lambda})$.

If $U_i^{\mathrm{C}}(\mathbf{Q},\boldsymbol{\lambda}) \geq U_i^{\mathrm{D}}(\mathbf{Q},\boldsymbol{\lambda})$, sets the bid $\mathbf{Q_{i,j}}(\tau) = (1, P_{i,j}^*(\lambda_j^2(\tau))$ to the target PU j;

For any other PU $k \neq j$, sets the bid $\mathbf{Q_{i,k}}(\tau) = (0,0)$.

Else sets $\mathbf{Q_{i,j'}}(\tau) = (1,0)$; For any other PU $k \neq j'$, sets $\mathbf{Q_{i,k}}(\tau) = (0,0)$.

Output: The new bid $\mathbf{Q_{i,j}}(\tau) = (C_{i,j}(\lambda_j^1(\tau), P_{i,j}(\lambda_j^2(\tau))$ to each PU.

At a PU $j \in \{1,\ldots,M\}$:

Input: Collects the bid $\mathbf{Q_{i,j}}(\tau) = (C_{i,j}(\lambda_j^1(\tau), P_{i,j}(\lambda_j^2(\tau))$ from each player $i \in \{1,\ldots,N\}$.

Calculates the excess channel demand by $E_j^1(\lambda_j^1(\tau)) = \sum_{i=1}^N C_{i,j}(\lambda_j^1(\tau)) - K_j$;

Calculates the excess power demand by $E_j^2(\lambda_j^2(\tau)) = \sum_{i=1}^N P_{i,j}(\lambda_j^2(\tau)) - P_{U_j}$;

If $E_j^1(\lambda_j^1(\tau)) > 0$ and $E_j^2(\lambda_j^2(\tau)) > 0$

$\hat{C_{i,j}}(\lambda_j^1(\tau)) = 0$, $\hat{P_{i,j}}(\lambda_j^2(\tau)) = 0$, $\forall i \in \{1,2,\ldots,N\}$;

$\lambda_j^1(\tau+1) = \lambda_j^1(\tau) + \mu_j^1$, $\lambda_j^2(\tau+1) = \lambda_j^2(\tau) + \mu_j^2$;

Else if $E_j^1(\lambda_j^1(\tau)) > 0$ and $E_j^2(\lambda_j^2(\tau)) \leq 0$

$\hat{C_{i,j}}(\lambda_j^1(\tau)) = 0$, $\hat{P_{i,j}}(\lambda_j^2(\tau)) = 0$, $\forall i \in \{1,2,\ldots,N\}$;

$\lambda_j^1(\tau+1) = \lambda_j^1(\tau) + \mu_j^1$, $\lambda_j^2(\tau+1) = \lambda_j^2(\tau)$;

Else if $E_j^1(\lambda_j^1(\tau)) \leq 0$ and $E_j^2(\lambda_j^2(\tau)) > 0$

$\hat{C_{i,j}}(\lambda_j^1(\tau)) = 1$, $\hat{P_{i,j}}(\lambda_j^2(\tau)) = \max(0, P_{U_j} - \sum_{k=1,k\neq i}^{N} P_{k,j}(\lambda_j^2(\tau)))$, for SU i with $C_{i,j}(\lambda_j^1(\tau)) = 1$;

$\lambda_j^1(\tau+1) = \lambda_j^1(\tau)$, $\lambda_j^2(\tau+1) = \lambda_j^2(\tau) + \mu_j^2$;

Else

$\hat{C_{i,j}}(\lambda_j^1(\tau)) = C_{i,j}(\lambda_j^1(\tau))$, $\hat{P_{i,j}}(\lambda_j^2(\tau)) = P_{i,j}(\lambda_j^2(\tau))$, $\forall i \in \{1,2,\ldots,N\}$;

For SU i with $C_{i,j}(\lambda_j^1(\tau)) = 0$ and $C_{i,j}(\lambda_j^1(\tau-1)) = 1$, sets $\hat{C_{i,j}}(\lambda_j^1(\tau')) = 0$, $\hat{P_{i,j}}(\lambda_j^2(\tau')) = 0$, $\forall \tau' \in \{0,1,\ldots,\tau-1\}$;

Output: The new price vector $\boldsymbol{\lambda_j}(\tau+1) = (\lambda_j^1(\tau+1), \lambda_j^2(\tau+1))$ to all SUs.

Iterates until the price vectors of all the PUs converge at $\tau = T$, then proceeds to the final step.

Final Step

For SU i with $\hat{P_{i,j}}(\lambda_j^2(T)) \neq 0$, each PU j updates the cumulative clinch $\hat{P_{i,j}}(\lambda_j^2(T))$ by (21);

Calculates the quantities of the channel and power that are assigned to each SU i by (22).

D. Practical Issues of the Proposed Auction Mechanism

In practice, the proposed auction algorithm can also be applied to the scenarios with unbalanced supply and demand. For example, if the number of the primary channels is less than the number of the SUs, i.e., the demand exceeds the supply, the PUs in inadequate supply would continually raise their channel prices. With the increase of the channel prices, some SUs would gradually quit the auction due to non-positive utility. When the number of the SUs staying in the auction equals to the number of the channels, the channel auction converges after finite iterations. On the contrary, if the number of the channels is larger than the number of the SUs, i.e., the supply exceeds the demand, they would be some channels that are not chosen by any SUs when the auction converges. This case can be viewed as a special case where the PUs only takes out part of the channels (equalling to the number of the SUs) for sale and leaves the surplus channels for their own use.

In this paper, we assume that the channels change slowly and the channel gain is stable within each frame. Note that for slow-fading channel, the duration of one frame or the channel coherence time T_c is relative large (typically on the order of milliseconds). Assume that each PU uses a control channel (non-overlapping with each other) to transmit auction signalling including the bids from the SUs and the prices from the PU, and the bids from the SUs to the same PU are sent in a TDM form. In particular, in auction slot, the PUs first broadcast their channel and power price $\boldsymbol{\lambda_j} = (\lambda_j^1, \lambda_j^2)$, and then the SUs send the quantities of the channel and power $\mathbf{Q_{i,j}} = (C_{i,j}, P_{i,j})$ they demand to the preferred PU. Both $\boldsymbol{\lambda_j}$ and $\mathbf{Q_{i,j}}$ are several bits enough. In practice, the SUs may not select lots of PUs for saving the exchanged information, e.g., each SU averagely selects 2–3 PUs. Therefore, for an auction with 2 PUs, 100 SUs and 200 iterations, the overhead is less than 10 ms, which is tolerable compared with the size of a frame. Since the bids from different SU may arrive at the PU at different time, the proposed auction algorithm can also run in a asynchronous way. At each auction clock, the PU collects the new bids until a timeout value $\overline{T}$ has passed. For the SUs whose bids has been received, the PU uses their new bids; For other SUs, the PU uses the most recent bids heard from them.

To employ auction, channel station information (CSI) is needed. For slow-fading channels, training-based channel estimation scheme at the receiver is very common. The CSI of the link from a PT/ST to its PR/SR is easy to be obtained due to the fact that both PT/ST and PR/SR are within the same system. For the CSI from a PU to a SU, a sequence containing training symbols may be periodically sent from each PU in a broadcast form. If the SUs catch the sequence and perform channel estimation, they could send back the CSI information so that the PUs have the knowledge of the channel condition between them and the SUs. The feedback of the CSI information from the SUs to each PU can be carried in two ways:

i) feeding back the CSI in a TDM form.
ii) all the SUs send back the CSI to the PU simultaneously in a CDM form. Therefore, the time used for feeding back the CSI could be greatly reduced, compared to the TDM form. Before sending out the CSI, a sort of orthogonal codes could be multiplied to the CSI. That is, each CSI from a SU to a PU is first multiplied with a sequence (like the orthogonal spreading sequences in a CDMA system), then all CSIs from all SUs could be sent simultaneously to a PU, given that the multiplied sequences for each CSI of the SU are orthogonal to each other. Although a PU will receive all CSIs at the same time, and all CSIs will be mixed together (added together at the PU), the PU could use different orthogonal sequences to match (multiply again) the received sequences (CSIs), and therefore, each CSI could be obtained separately.

V. Theoretic Analysis

First, we specify a generic economic model: M auctioneers wish to allocate K commodities among N bidders. The first I commodities are indivisible and the last $K-I$ commodities are divisible. The available supply of K commodities at auctioneer j is $\mathbf{S_j} = (S_j^1, \ldots, S_j^K)$. For $k = 1, \ldots, I$, $S_j^k \in \mathbb{Z}_{++}$; For $k = I+1, \ldots, K$, $S_j^k \in \mathbb{R}_{++}$. The announced price vector of auctioneer j is $\boldsymbol{\lambda_j} = (\lambda_j^1, \ldots, \lambda_j^K) \in \mathbb{R}_+$. For any commodity $k \in \{1, \ldots, K\}$, the announced price from all the auctioneers is $\boldsymbol{\lambda^k} = (\lambda_1^k, \ldots, \lambda_M^k)$. The allocation of auctioneer j to bidder i is $\mathbf{A_{i,j}} = (A_{i,j}^1, \ldots, A_{i,j}^K)$. For $k = 1, \ldots, I$, $A_{i,j}^k \in \mathbb{Z}_+$; For $k = I+1, \ldots, K$, $A_{i,j}^k \in \mathbb{R}_+$. The demand of bidder i from auctioneer j at price $\boldsymbol{\lambda}$ is $\mathbf{Q_{i,j}}(\boldsymbol{\lambda}) = (Q_{i,j}^1(\boldsymbol{\lambda}^1), \ldots, Q_{i,j}^K(\boldsymbol{\lambda}^K))$. For $k = 1, \ldots, I$, $Q_{i,j}^k \in \mathbb{Z}_+$; For $k = I+1, \ldots, K$, $Q_{i,j}^k \in \mathbb{R}_+$. The payment of bidder i to auctioneer j is $\mathbf{V_{i,j}} = (V_{i,j}^1, \ldots, V_{i,j}^K) \in \mathbb{R}_+$. For each commodity $k \in \{1, \ldots, K\}$ received from auctioneer j, bidder i has a satisfaction function $F_{i,j}^k(Q_{i,j}^k) \in \mathbb{R}$.

We now discuss two important properties of the proposed auction algorithm.

A. Existence of a Walrasian Equilibrium

Definition 1. [31]: A Walrasian equilibrium is a $M \times K$ price vector

$$\boldsymbol{\lambda}^* = \begin{pmatrix} \lambda_1^{1*} & \lambda_1^{2*} & \ldots & \lambda_1^{K*} \\ . & . & & . \\ . & . & & . \\ . & . & & . \\ \lambda_M^{1*} & \lambda_M^{2*} & \ldots & \lambda_M^{K*} \end{pmatrix}$$

and a $N \times M \times K$ allocation vector

$$\mathbf{A}^* = \begin{pmatrix} \mathbf{A}_{\mathbf{1,1}}^* & \mathbf{A}_{\mathbf{1,2}}^* & \ldots & \mathbf{A}_{\mathbf{1,M}}^* \\ . & . & & . \\ . & . & & . \\ . & . & & . \\ \mathbf{A}_{\mathbf{N,1}}^* & \mathbf{A}_{\mathbf{N,2}}^* & \ldots & \mathbf{A}_{\mathbf{N,M}}^* \end{pmatrix},$$

such that

$$\mathbf{Q}(\boldsymbol{\lambda}^*) = \begin{pmatrix} \mathbf{Q_{1,1}}(\boldsymbol{\lambda}^*) & \mathbf{Q_{1,2}}(\boldsymbol{\lambda}^*) & \ldots & \mathbf{Q_{1,M}}(\boldsymbol{\lambda}^*) \\ . & . & & . \\ . & . & & . \\ . & . & & . \\ \mathbf{Q_{N,1}}(\boldsymbol{\lambda}^*) & \mathbf{Q_{N,2}}(\boldsymbol{\lambda}^*) & \ldots & \mathbf{Q_{N,M}}(\boldsymbol{\lambda}^*) \end{pmatrix} = \mathbf{A}^*,$$

and $S_j^k = \sum_{i=1}^N A_{i,j}^{k*}$, $\forall j \in \{1, \ldots, M\}$, $\forall k \in \{1, \ldots, K\}$.

According to Definition 1, when the auction reaches a Walrasian equilibrium, the assignment of each commodity at each auctioneer to each bidder equals to its request. Meanwhile, the aggregate demand of all the bidders for each commodity at each auctioneer equals to the supply of that commodity at that auctioneer.

Definition 2: The satisfaction function $F_{i,j}^k(Q_{i,j}^k)$, $\forall k \in \{1,\ldots,I\}$, is said to satisfy gross substitutes condition if, for any two announced price vector $\boldsymbol{\lambda^k}$ and $\boldsymbol{\lambda^{k'}}$ such that $\boldsymbol{\lambda^{k'}} \geq \boldsymbol{\lambda^k}$, $Q_{i,j}^k(\boldsymbol{\lambda^{k'}}) \geq Q_{i,j}^k(\boldsymbol{\lambda^k})$ for any auctioneer $j \in \{1,\ldots,M\}$ such that $\lambda_j^{k'} = \lambda_j^k$.

Lemma 1: An auction for hybrid divisible/indivisible commodities has a Walrasian equilibrium if it satisfies:

1) *Pure private values*: Bidder i's satisfaction function $F_{i,j}^k(Q_{i,j}^k)$ is a function of the demand $Q_{i,j}^k$, and it does not depend on any information about other bidders.
2) *Quasilinearity*: Bidder i's satisfaction from receiving the demand $Q_{i,j}^k$ in return for the payment $V_{i,j}^k$ is given by $F_{i,j}^k(Q_{i,j}^k) - V_{i,j}^k$.
3) *Monotonicity*: Bidder i's satisfaction function $F_{i,j}^k(Q_{i,j}^k)$ is increasing, i.e., if $Q_{i,j}^{k'} > Q_{i,j}^k$, $F_{i,j}^k(Q_{i,j}^{k'}) > F_{i,j}^k(Q_{i,j}^k)$.
4) *Concavity*: For any divisible commodity $k \in \{I+1,\ldots,K\}$, bidder i's satisfaction function $F_{i,j}^k(Q_{i,j}^k)$ is concave.
5) *Substitutes condition*: For any indivisible commodity $k \in \{1,\ldots,I\}$, bidder i's satisfaction function $F_{i,j}^k(Q_{i,j}^k)$ satisfies gross substitutes condition.

Theorem 1: The proposed channel and power auction has a Walrasian equilibrium.

Proof: If the SU selects direct transmission and only purchases the channel, its satisfaction from the received channel is represented by the achievable rate $R_{i,j}^{\mathrm{D}}(C_{i,j})$. If it selects cooperative transmission, its satisfaction is represented by the achievable rate $R_{i,j}^{\mathrm{C}}(P_{i,j})$.

Pure private values: For the SU in cooperative transmission, its satisfaction function, i.e. $R_{i,j}^{\mathrm{C}}(P_{i,j})$, is a function of the power demand $P_{i,j}$, and $P_{i,j}$ is uniquely determined by the announced price $\boldsymbol{\lambda}$. As long as $\boldsymbol{\lambda}$ is fixed, $R_{i,j}^{\mathrm{C}}(P_{i,j})$ remains unchanged, regardless of the power demands of other SUs; For the SU in direct transmission, its satisfaction function, i.e. $R_{i,j}^{\mathrm{D}}(C_{i,j})$, is defined as:

$$R_{i,j}^{\mathrm{D}}(C_{i,j}) = \begin{cases} R_{i,j}^{\mathrm{D}}, & \text{if } C_{i,j} = 1; \\ 0, & \text{if } C_{i,j} = 0. \end{cases} \tag{25}$$

Clearly, it does not depend on other SUs' channel demands.

Quasilinearity: According to (10), the utility function $U_{i,j}^{\mathrm{C}}(\mathbf{Q_{i,j}}, \boldsymbol{\lambda_j})$ of the SU in cooperative transmission is quasilinear in its payment. Similarly, it is observed from (12) that the utility function $U_{i,j}^{\mathrm{D}}(\mathbf{Q_{i,j}}, \boldsymbol{\lambda_j})$ of the SU in direct transmission is also quasilinear in its payment.

Monotonicity: As can be seen that the satisfaction function $R_{i,j}^{\mathrm{C}}(P_{i,j})$ of the SU in cooperative transmission increases with respect to $P_{i,j}$ for the sake that $\partial R_{i,j}^{\mathrm{C}}(P_{i,j})/\partial P_{i,j} > 0$. On the other hand, for SU i in direct transmission, if it does not choose PU j's channel, then $C_{i,j} = 0$ and $R_{i,j}^{\mathrm{D}}(C_{i,j}) = 0$; Otherwise $C_{i,j} = 1$ and $R_{i,j}^{\mathrm{D}}(C_{i,j}) > 0$.

Concavity: For the SU in cooperative transmission, we have $\partial^2 R_{i,j}^{\mathrm{C}}(P_{i,j})/\partial^2 P_{i,j} < 0$. Hence, the satisfaction function $R_{i,j}^{\mathrm{C}}(P_{i,j})$ is concave.

Substitutes condition: For any SU i in direct transmission, it is found that if the channel prices of some PUs are increased while the channel prices of all other PUs are fixed, SU i's channel demands from the PUs whose prices are fixed are non-decreasing.

Therefore, there exists a Walrasian equilibrium for the proposed auction. ■

B. Convergence

Theorem 1 shows the existence of a Walrasian equilibrium for the proposed auction algorithm, but it does not tell us how this auction converges to a Walrasian equilibrium price vector $\boldsymbol{\lambda}^*$. As previously mentioned, the price adjustment of the proposed auction is directly controlled by the excess demand. If there is excess demand (e.g. for the power) at PU j, i.e. $E_j^2(\lambda_j^2(\tau)) > 0$, the price is increased by μ_j^2. Otherwise, it is fixed. In fact, this ascending price adjustment mechanism can be viewed as a discrete version of the Walrasian tâtonnement [32], i.e.,

$$\lambda_j^k(\tau+1) = \lambda_j^k(\tau) + \dot{\lambda_j^k}(\tau), \tag{26}$$

where we have

$$\dot{\lambda_j^k}(\tau) = \begin{cases} \mu_j^k, & \text{if } E_j^k(\lambda_j^k(\tau)) > 0; \\ 0, & \text{otherwise.} \end{cases} \tag{27}$$

Theorem 2: Starting from any sufficiently small price vector $\boldsymbol{\lambda}(0)$, the proposed auction algorithm converges to a Walrasian equilibrium price vector $\boldsymbol{\lambda}^*$ in finite iterations.

Proof: In terms of the excess demand and the Walrasian tâtonnement, we construct the following *Lyapunov function*:

$$L(\boldsymbol{\lambda}) = \sum_{j=1}^{M} \boldsymbol{\lambda_j} \cdot \mathbf{S_j} + \sum_{i=1}^{N} U_i(\mathbf{Q_i}, \boldsymbol{\lambda}). \tag{28}$$

Assume that there are N_1, $0 \leq N_1 \leq N$, SUs select cooperative transmission, and $N - N_1$ SUs select direct transmission. Let k_j^{C}, $0 \leq k_j^{\mathrm{C}} \leq K_j$, denote the channel supply of PU j for the SUs in cooperative transmission, which satisfies $\sum_{j=1}^{M} k_j^{\mathrm{C}} = N_1$. Further, let $\mathbf{S_j^{\mathrm{C}}} = (k_j^{\mathrm{C}}, P_{U_j})$ represent the supply of PU j for the SUs in cooperative transmission. Thereby, the Lyapunov function can be re-written as:

$$\begin{aligned} L(\boldsymbol{\lambda}) &= \sum_{j=1}^{M} \boldsymbol{\lambda_j} \cdot \left[\begin{pmatrix} k_j^{\mathrm{C}} \\ P_{U_j} \end{pmatrix} + \begin{pmatrix} K_j - k_j^{\mathrm{C}} \\ 0 \end{pmatrix} \right] + \sum_{i=1}^{N_1} U_i^{\mathrm{C}}(\mathbf{Q_i}, \boldsymbol{\lambda}) \\ &\quad + \sum_{i=N_1+1}^{N} U_i^{\mathrm{D}}(\mathbf{Q_i}, \boldsymbol{\lambda}) \\ &= \sum_{j=1}^{M} \boldsymbol{\lambda_j} \cdot \begin{pmatrix} k_j^{\mathrm{C}} \\ P_{U_j} \end{pmatrix} + \sum_{i=1}^{N_1} U_i^{\mathrm{C}}(\mathbf{Q_i}, \boldsymbol{\lambda}) + \sum_{j=1}^{M} \boldsymbol{\lambda_j} \cdot \begin{pmatrix} K_j - k_j^{\mathrm{C}} \\ 0 \end{pmatrix} \\ &\quad + \sum_{i=N_1+1}^{N} U_i^{\mathrm{D}}(\mathbf{Q_i}, \boldsymbol{\lambda}) \\ &= \sum_{j=1}^{M} \boldsymbol{\lambda_j} \cdot \mathbf{S_j^{\mathrm{C}}} + \sum_{i=1}^{N_1} U_i^{\mathrm{C}}(\mathbf{Q_i}, \boldsymbol{\lambda}) \\ &\quad + \sum_{j=1}^{M} \boldsymbol{\lambda_j} \cdot (\mathbf{S_j} - \mathbf{S_j^{\mathrm{C}}}) + \sum_{i=N_1+1}^{N} U_i^{\mathrm{D}}(\mathbf{Q_i}, \boldsymbol{\lambda}) \\ &\triangleq L^{\mathrm{C}}(\boldsymbol{\lambda}) + L^{\mathrm{D}}(\boldsymbol{\lambda}) \end{aligned} \tag{29}$$

where $L^{\mathrm{C}}(\boldsymbol{\lambda})$ and $L^{\mathrm{D}}(\boldsymbol{\lambda})$ represent the Lyapunov function of the SUs select cooperative and direct transmission, respectively.

The iterative interactions between the PUs and the SUs would finally end with the optimal $\boldsymbol{\lambda}^*$, $\mathbf{Q}^*$, $\mathbf{S}_\mathbf{j}^{\mathrm{C}*}$, and N_1^*, at which the Lyapunov function $L(\cdot)$ is minimized and the auction converges.

For the SUs in cooperative transmission, the subgradient of $L^{\mathrm{C}}(\cdot)$ at $\boldsymbol{\lambda_j}$ equals to

$$\mathbf{S}_\mathbf{j}^{\mathrm{C}} - \sum_{i=1}^{N_1} \mathbf{Q}_{\mathbf{i},\mathbf{j}}(\boldsymbol{\lambda_j}) = -\mathbf{E}_\mathbf{j}^{\mathrm{C}}(\boldsymbol{\lambda_j}), \tag{30}$$

where $\mathbf{E}_\mathbf{j}^{\mathrm{C}}(\boldsymbol{\lambda_j})$ denotes the excess demand of the SUs in cooperative transmission from PU j. For any $\boldsymbol{\lambda_j} \neq \boldsymbol{\lambda_j^*}$, $\forall j \in \{1, \ldots, M\}$, we have $\dot{L}^{\mathrm{C}}(\boldsymbol{\lambda_j^*}) = 0$ and $\dot{L}^{\mathrm{C}}(\boldsymbol{\lambda_j}) < 0$. The ascending price adjustment process continues as long as $\boldsymbol{\lambda}(\tau+1) \neq \boldsymbol{\lambda}(\tau)$. Finally, it terminates at $\boldsymbol{\lambda}^*$, at which $\mathbf{E}^{\mathrm{C}}(\boldsymbol{\lambda}^*) = \mathbf{0}$, and the $L^{\mathrm{C}}(\cdot)$ is minimized.

For the SUs in direct transmission, under the substitutes condition, the Lyapunov function $L^{\mathrm{D}}(\cdot)$ is a submodular function [33]. Therefore, for any $\boldsymbol{\lambda}$ and $\boldsymbol{\lambda}'$, it has

$$L^{\mathrm{D}}(\boldsymbol{\lambda} \vee \boldsymbol{\lambda}') + L^{\mathrm{D}}(\boldsymbol{\lambda} \wedge \boldsymbol{\lambda}') \leq L^{\mathrm{D}}(\boldsymbol{\lambda}) + L^{\mathrm{D}}(\boldsymbol{\lambda}'), \tag{31}$$

where $\boldsymbol{\lambda} \vee \boldsymbol{\lambda}'$ and $\boldsymbol{\lambda} \wedge \boldsymbol{\lambda}'$ denote the coordinate-by-coordinate maximum and minimum of $\boldsymbol{\lambda}$ and $\boldsymbol{\lambda}'$, respectively. It can be proved that $L^{\mathrm{D}}(\cdot)$ is minimized at Walrasian equilibrium price vectors. Whenever $\boldsymbol{\lambda}(\tau)$ is not a Walrasian equilibrium price vector, it increases to a next price vector $\boldsymbol{\lambda}(\tau+1)$ such that $L^{\mathrm{D}}(\boldsymbol{\lambda}(\tau+1)) < L^{\mathrm{D}}(\boldsymbol{\lambda}(\tau))$.

When both $L^{\mathrm{C}}(\cdot)$ and $L^{\mathrm{D}}(\cdot)$ is minimized, the auction converges to a Walrasian equilibrium price vector $\boldsymbol{\lambda}^*$. ■

VI. Simulation Results

In this section, we present simulation results to demonstrate the performance of the proposed dynamic spectrum access and power allocation algorithm. We consider a scenario as shown in Fig. 4, where there are two PUs and six SUs in the network. PU 1 has 4 channels and PU 2 has 2 channels. The channel gains are $(\frac{0.097}{d^\gamma})^{\frac{1}{2}}$, where d is the distance between two nodes, and the path-loss exponent is $\gamma = 4$. The noise variance is $\sigma^2 = 10^{-13}$. The transmit power of each PU is 2 W. The transmit power of each SU is 0.1 W. The initial power price of both PUs is 0.8. The initial channel price of both PUs is 1. The step size for updating the power price is 0.5. The step size for updating the channel price is 0.2.

With the above configuration, throughout the auction process, all the SUs all the time select cooperative transmission mode. Among them, SU 1∼SU 3 select PU 1 as the relay, SU 5 and SU 6 select PU 2 as the relay, and the choice of SU 4 varies between two PUs as shown in Fig. 5. From the very beginning to the 74-*th* iteration, both PUs bring the same cooperative utility for SU 4 due to their similar initial settings, and similar channel and power price evolution. SU 4 then randomly selects PU 1 for cooperation during this period. At the 75-*th* iteration, PU 2's power price stops ascending as the supply meets the demand, while PU 1's power price continually increases. SU 4 therefore turns to PU 2 at the 75-*th* iteration. Thereafter, as the cooperative utilities incurred by two PUs are very close, SU 4 oscillates between PU 1 and PU 2, and finally fixes at PU 1 after 165 iterations.

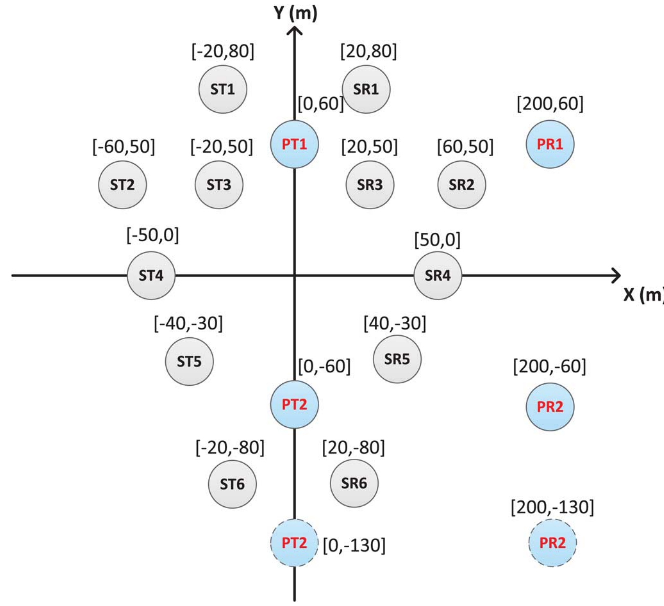

Fig. 4. A two-PU six-SU simulation network.

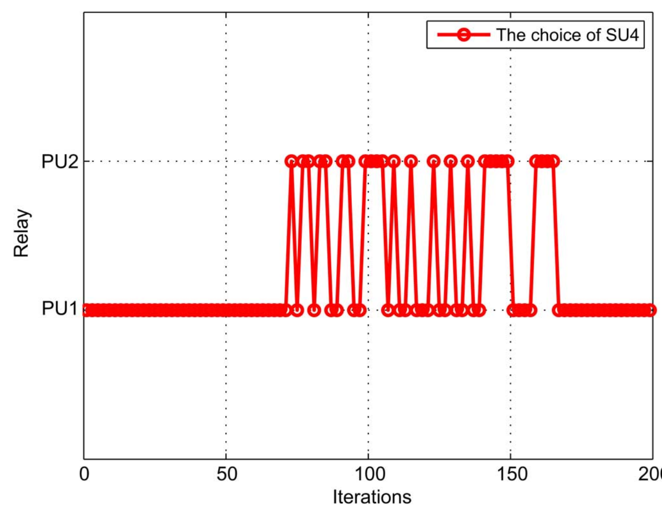

Fig. 5. Relay selection of SU 4.

The convergence behavior of two PUs' four prices is showed in Fig. 6. It is observed that these four prices converge at different speed, and the entire auction converges after 165 iterations. Compared the equilibrium points (i.e. the optimal prices) of two PUs, we find that the optimal power price of PU 1 is higher than that of PU 2. It indicates that the power competition at PU 1 is much stronger than at PU 2, which leads to more iterations and a higher equilibrium price. Note that exclude SU 4, there are always 3 SUs compete for the power at PU 1, while there are only 2 SUs request the power from PU 2. In addition, it is noticed that the channel price of PU 1 remains unchanged throughout the auction process. As there are at most 4 SUs (i.e. SU 1∼SU 4) bidding for PU 1's channel, which is always no more than its supply. For the channel price of PU 2, within the period from the 75-*th* iteration to the 165-*th* iteration, it ascends when SU 4 selects PU 2, and remains static when SU 4 turns back to PU 1.

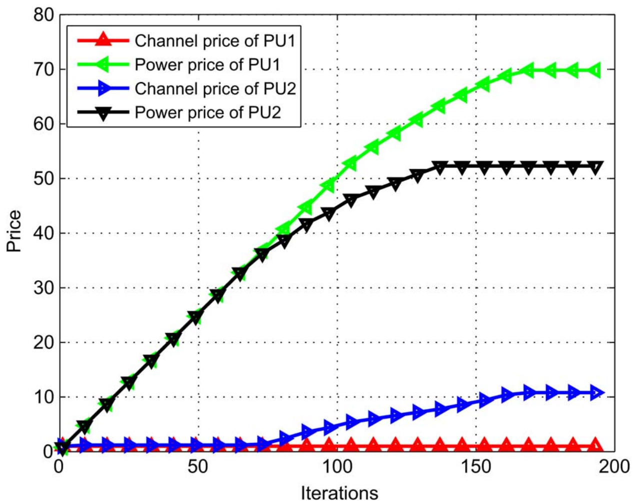

Fig. 6. Convergence of two PUs' prices.

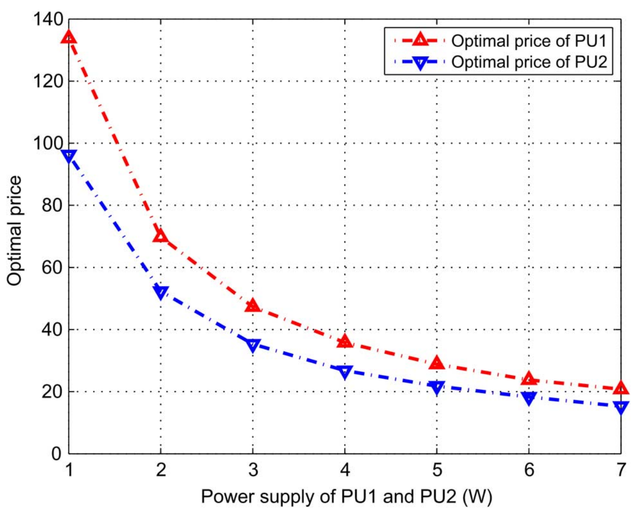

Fig. 7. Optimal power price of each PU.

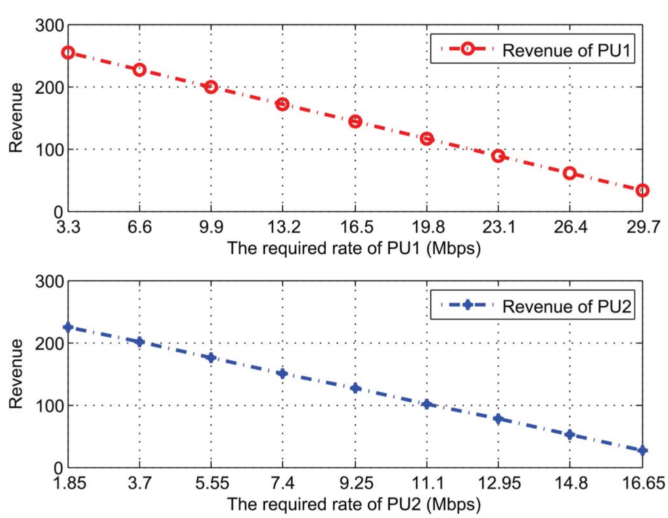

Fig. 8. PU's revenue vs. its rate requirement.

We adjust the transmit power supply of each PU within a range of [1 W, 7 W], and keep other settings unchanged. It is seen in Fig. 7, that the optimal power price of each PU increases with the decrease of its power supply. This is due to the fact that the less power supply at a PU, the stronger power competition at that PU, the smaller possibility that the supply can meet the total demand of the SUs, and the higher optimal price would be, and vice versa. It tells a story that the more rare a commodity, the more precious it is, and the higher price it would ask for.

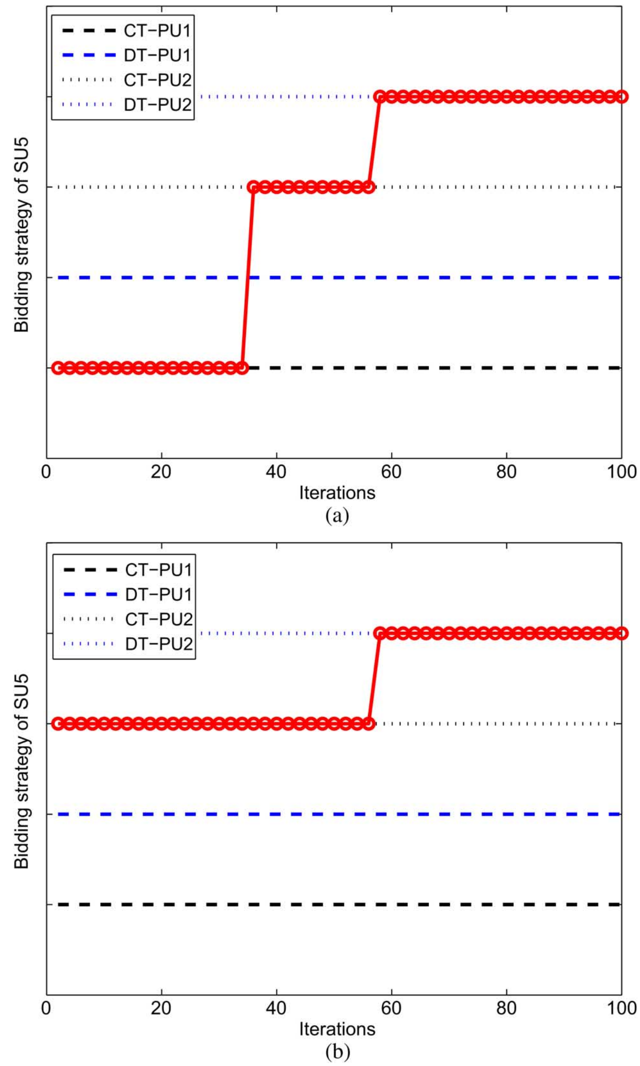

Fig. 9. Evolution of the bidding strategy. (a) SU 5; (b) SU 6.

Fig. 8 shows the relationship of PU's revenue with its rate requirement. As can be seen that PU's revenue decreases with the increase of its rate requirement. The higher rate requirement, the smaller portion of the time slot the PU takes out for sale, and the less revenue it earns. As PU 1 has more channels than PU2, for the same rate requirement, PU 1 itself requires a smaller portion α than PU 2, thus achieving more revenue than PU 2. When the required rate of both PUs respectively reach to 29.7 Mbps and 16.65 Mbps, both PUs would use all the resource themselves and do not provide relaying service for the SUs any more.

We now move PT 2 and PR 2 to (0 m, -130 m) and (200 m, -130 m), respectively. In fact, the change of PU 2's location does not affect the choices of SU 1$\sim$SU 3, and they still select PU 1 as the relay for the sake that PU 1 is much closer to them. SU 4 also sticks to cooperative transmission mode, but no longer wavers between PU 1 and PU 2. Instead, it selects the closer PU 1 all the time. Since SU 5 and SU 6 cannot always achieve a

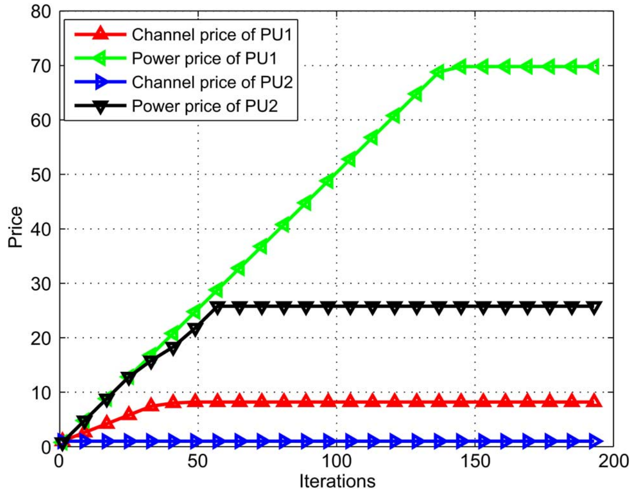

Fig. 10. Convergence of two PUs' prices after PU 2's movement.

maximum utility from the cooperation from PU 2 which is now moved away from them, they dynamically adjust their bidding strategies during the auction process. Fig. 9 plots the evolution of their bidding strategies. It is seen that SU 5 first selects cooperative transmission (CT) and PU 1 as the relay, then changes to cooperative transmission with PU 2, and is finally stable at direct transmission (DT) with PU 2's channel. As for SU 6, since PU 1 is too far away from it, it centralizes on PU 2. When cooperation from PU 2 no long brings a maximum utility, it changes to direct transmission via PU 2's channel. In a word, PU 2's movement decreases the cooperative utilities achieved by SU 5 and SU 6, which causes them to substitute direct transmission for cooperative transmission.

Fig. 10 shows the convergence performance of the proposed auction after PU 2's movement. Compared with its original performance shown in Fig. 6, we find that the channel price of PU 2, rather than that of PU 1, remains at the original price all the time. The channel price of PU 1 ascends when SU 5 joins PU 1's channel competition. When the auction terminates, SU 5 and SU 6 both select direct transmission and choose PU 2's channel, PU 2 thus only sell out its channels, with all the power left for itself. In this case, the convergent power price of PU 2 is meaningless to PU 2, and its revenue from power trading is actually zero.

Finally, we keep the initial channel and power price of PU 1 unchanged, and increase the initial channel and power price of PU 2 2 and 4 times, respectively. The convergence performance and the evolution of SU 5 and SU 6's bidding strategy (increasing PU 2' prices only impacts SU 5 and SU 6's choice) are shown in Fig. 11 and 12. It is observed that, compared with the original price settings, the equilibrium points of four prices as well as the choices of both SUs remain unchanged. Since the proposed auction algorithm uses the ascending price adjustment rule, it converges to the same Walrasian equilibrium price vector as long as starting from a sufficiently small price vector, as shown in Theorem 2.

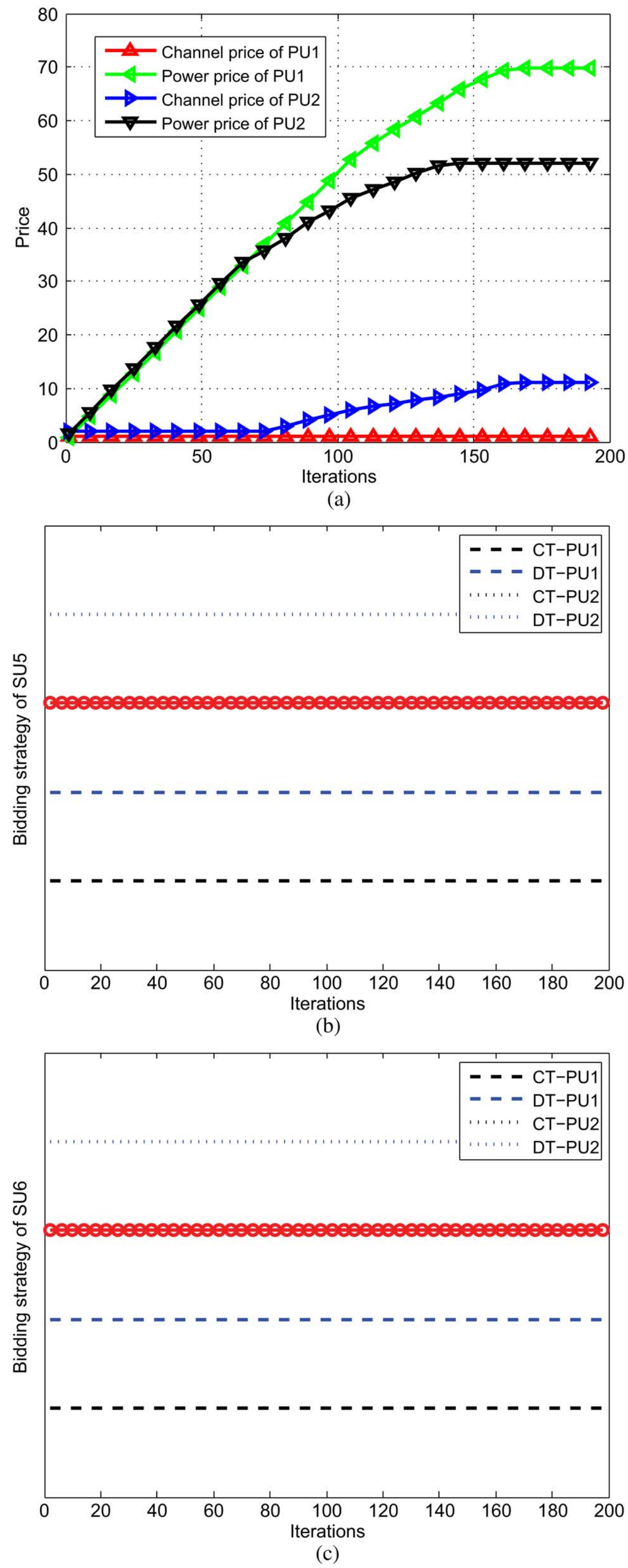

Fig. 11. Impacts of initial price: $\lambda_2^1 = 2$, $\lambda_2^2 = 1.6$. (a) Convergence performance; (b) SU 5's bidding strategy; (c) SU 6's bidding strategy.

VII. Conclusion

In this paper, we addressed the dynamic spectrum access and power allocation problem under a new cooperative cognitive radio framework, where primary users use the under-utilized channel and transmit power to cooperatively relay data for secondary users, and thus earn revenue from the channel and power trading. The trading between primary users and secondary users

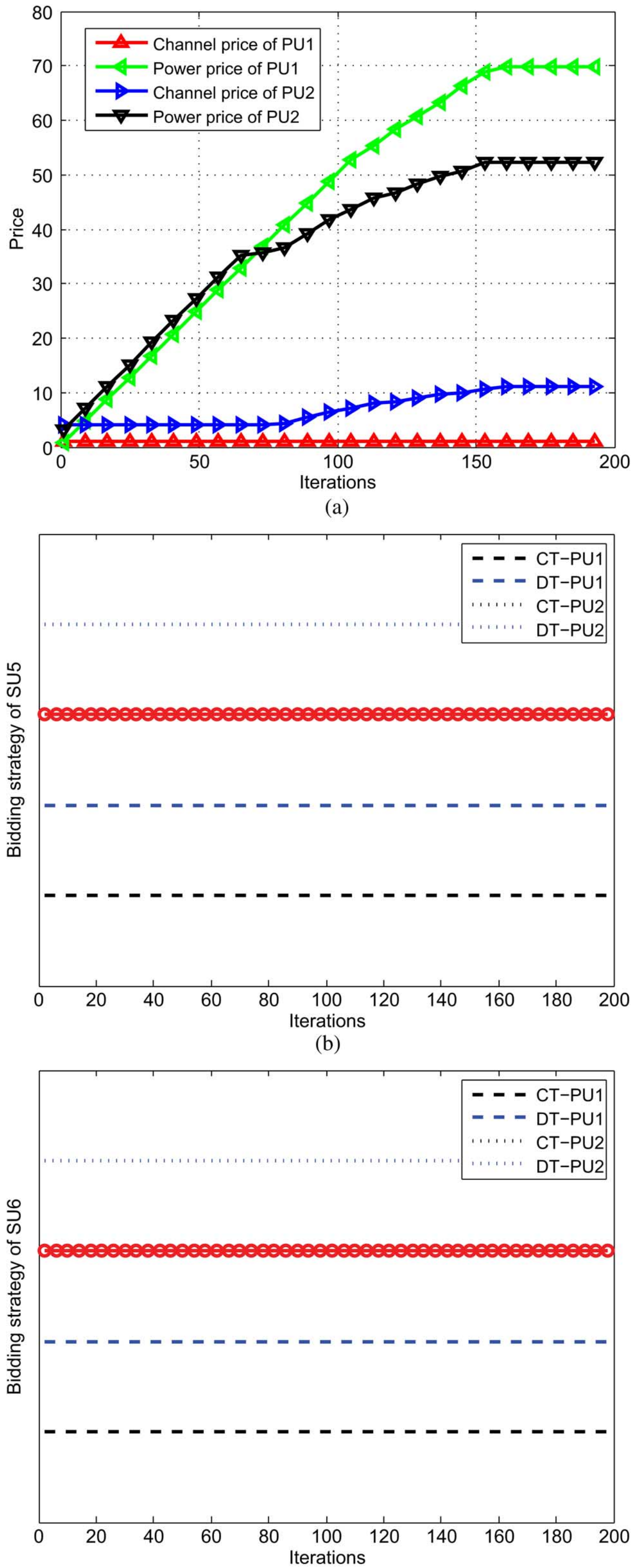

Fig. 12. Impacts of initial price: $\lambda_2^1 = 4$, $\lambda_2^2 = 3.2$. (a) Convergence performance; (b) SU 5's bidding strategy; (c) SU 6's bidding strategy.

is modeled as an auction with multiple auctioneers, multiple bidders and multiple commodities. The convergence performance of the proposed auction game is investigated and verified. The proposed auction algorithm focused on maximizing the aggregate rates of all the SUs, in which the fairness is ignored. In practice, both the global performance and the user fairness are required for different applications. Therefore, how to attain a tradeoff between them remains to be addressed. Moreover, we assume that the CSI is accurately measured and timely available for bidding process, we propose to relax this condition and analyze the relationship between the performance degradation and channel estimation accuracy.

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