# Dynamic Matching Based Distributed Spectrum Trading in Multi-Radio Multi-Channel CRNs

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***Abstract*—Spectrum trading not only improves spectrum utilization but also benefits both secondary users (SUs) with more accessing opportunities and primary users (PUs) with monetary gains. Although existing centralized designs consider the special features of spectrum trading (e.g., frequency reuse, interference mitigation, multi-radio multi-channel transmissions, etc.), they have to deploy new infrastructure, deal with extra control overhead, have scalability issues, and may miss many instantaneous opportunities. To address those issues, in this paper, we propose a novel dynamic matching based distributed spectrum trading (DMDST) scheme in multi-radio multi-channel cognitive radio (CR) networks. We employ conflict graph to characterize interference relationship among SUs with multiple CR radios, and formulate the centralized PUs' revenue maximization problem under multiple constrains. In view of the NP-hardness of solving the problem and no existence of centralized entity, we develop the DMDST algorithms based on conflict graph observed by PUs, solve the problem via dynamic matching with evolving preferences, and prove its stability. Through extensive simulations, we show that the results of proposed DMDST algorithm is close to the optimal one and outperforms other distributed algorithms without considering spectrum reuse.**

***Index Terms*—Distributed Spectrum Trading; Spectrum Reuse;Multi-Radio Multi-Channel; Dynamic Matching; Spectrum Utilization; Revenue**

## I. Introduction

The last decade has witnessed the dramatic proliferation of wireless networks and wireless services. This explosion of wireless applications creates an ever-increasing demand for more radio spectrum [1], [2], while the licensed spectrum bands are not fully utilized even in the most crowded region of cities [3]. Cognitive radio (CR) offers the promise of being a disruptive technology innovation to solve this dilemma. CR releases the spectrum from shackles of authorized licenses, and enables secondary users (SUs) to opportunistically access to the vacant licensed spectrum bands in either temporal or spatial domain [1], [2]. Due to the high economic values of spectrum, CR technology and opportunistic spectrum accessing have initiated the spectrum market, in which primary users (PUs) can sell/lease/auction their vacant spectrum for monetary gains, and SUs can purchase/rent/bid the available licensed spectrum to support their traffic demands [4], [5].

Different from common commodities, spectrum can be spatially reused, and this special feature of spectrum has promoted many research works on the centralized designs of spectrum trading [4]–[6]. For example, Zhou et al. in [4] proposed a incentive compatible spectrum trading mechanism where each SU has only one radio. Given SUs equipped with multiple radios, Li et al. in [6] studied economic-robust per-link based spectrum trading in multi-hop cognitive cellular network. Pan et al. in [5] further extended the design into session-based one, and investigated PUs' revenue maximization problem in multi-radio multi-channel (MRMC) cognitive radio networks (CRNs). Although the centralized spectrum trading design takes spectrum reuse into account, it needs the infrastructure deployment with extra economic and control cost, and the designated centralized spectrum traders (e.g., base stations) may add huge energy consumption in existing networks. In addition, the centralized spectrum trading designs may not capture instantaneous accessing opportunities well, and have scalability issues, when the network size of SUs increases.

Beyond the centralized spectrum trading designs, in existing literature, there are some interesting distributed spectrum trading schemes. For example, Xing et al. in [7] employed game theory to study the spectrum pricing issues in the spectrum market, where the goal of the multiple PUs is to maximize the monetary gains with their vacant spectrum, compete with each other to offer spectrum access to the SUs. Zhang et al. in [8] and Gu et al. in [9] employed many-to-one/student-project matching to share the spectrum trying to maximize the social welfare in CR networks/LTE-Unlicensed systems, respectively. However, most existing distributed spectrum trading designs have limited concern of spatial reuse, which might lead to monetary loss for PUs and missing valuable spectrum accessing opportunities for SUs. There is also a lack of distributed spectrum trading schemes in MRMC CRNs.

To address the issues above, in this paper, we propose a novel dynamic matching based distributed spectrum trading scheme (DMDST), which jointly considers spectrum reuse and MRMC features, and allows spectrum trading between PUs and SUs in distributed manners in MRMC CRNs. In DMDST, we employ dynamic matching to trade the spectrum with the

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objective to maximize PUs' revenues. Different from traditional matching [8], [9], the PU's preference list evolves, which depends on both SUs' bidding values and SUs' interference relationship observed by the PU. We mathematically model the problem, develop DMDST matching algorithm, prove its stability, and conduct performance evaluations. We found that the proposed scheme provides more accessing opportunities for SUs, increases the revenues of PUs, and improves spectrum utilization compared with existing distributed designs in MRMC CRNs. Our salient contributions are listed as follows.

- We consider a spectrum trading market consisting of PU and SU transmission pairs as shown in Figure 1. Conflict graph is employed to describe the SUs' and PUs' interference relationships (i.e., co-band interference and radio interference). We formulate the centralized optimization problem with the objective to maximizing PUs' revenues under both frequency reuse and MRMC transmission constraints according to the constructed conflict graph. Since there is no centralized spectrum trader and the formulated problem is a mixed integer nonlinear programming (MINLP), no classical solution exists.
- To pursuit feasible solutions in distributed manners, we exploit dynamic matching with preferences to propose a novel DMDST scheme. By jointly considering interference mitigation, spatial reuse, MRMC transmissions, and spectrum trading benefits in matching process. In DMDST, the SU lists its preferences over PUs' bands based on its potential transmission rate. The PU, who targets at maximizing its revenue, will accept as many SUs as possible, as long as those SUs have no mutual interferences. A PU lists its preferences over SUs based on his observations of SUs' conflicts. Moreover, the preference lists of PUs evolve during the matching procedure. In this paper, we mathematically present both PUs' and SUs' utility functions, develop a two-phase matching algorithm with evolving preferences of PUs, and prove its pairwise stability.
- Through extensive simulations, we show that the proposed DMDST outperforms other distributed spectrum trading algorithms without considering frequency reuse in MRMC CRNs, and the feasible solutions obtained by proposed algorithm are close to the optimal one in terms of the PUs' revenues and spectrum utilization improvement.

## II. Network Model

### A. Network Configuration

As shown in Figure 1, we consider a spectrum trading plaza consisting of $\mathcal{N} = \{1, 2, \cdots, n, \cdots, N\}$ SU transmission pairs, and $\mathcal{M} = \{1, 2, \cdots, m, \cdots, M\}$ PU transmission pairs operating on different spectrum bands. We assume each SU transmitter/receiver has several radio interfaces, and each PU pair owns one spectrum band. We denote the radio transceivers of SUs as $\mathcal{R} = \{1, 2, \cdots, r, \cdots, R\}$. That indicates SUs can access over $\mid \mathcal{R} \mid$ bands of PUs simultaneously. We also denote the unequal sized bandwidths of PUs' bands by $\mathcal{W} = \{W^1, W^2, \cdots, W^m, \cdots, W^M\}$. In addition, all available spectrum bands at one SU are as same as another SU in the network, i.e., every SU have opportunity to access all PUs$'$ bands in the network. To put it in a mathematical way, let $\mathcal{M}_i \subseteq \mathcal{M}$ represent the set of available bands at SU pair $i \in \mathcal{N}$, then $\mathcal{M}_i = \mathcal{M}_j$ if $j \in \mathcal{N}$ and $i \neq j$.

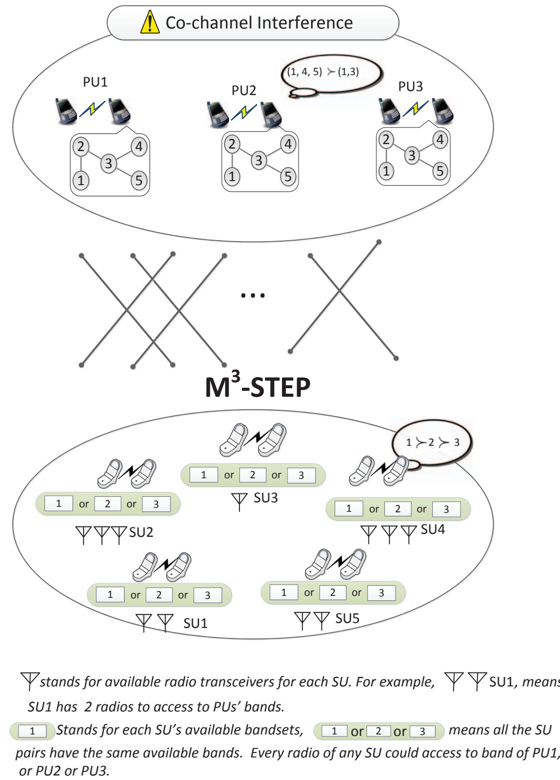


Fig. 1. Network Architecture for DMDST in MRMC CRNs.

In this spectrum market, PUs sell bands for monetary gains, and SUs purchase available bands to deliver data traffic. Here, SU $i \in \mathcal{N}$ has to reduce its transmission power over the band $k \in \mathcal{M}$ when service of PU$_k$ are active. To simplify the network model, we assume bidding values of all SUs are the same, e.g., \$1. Thus, from the SU's perspective, considering it has several accessible radio interfaces, it would like to choose the bands over which it can access maximum transmission rate; from the PU's perspective, considering spatial reuse, it would like to accommodate as many SUs as possible to receive maximum revenues.

### B. Other Related Models in Spectrum Trading

*1) SU's Transmission Range/Interference Range:* SUs can use a certain band with full power if there are no services of PUs are used over this band. We assume all SUs have the same full transmission power $P$. For power propagation gain, we used the model shown as [10]

$$g_i = \gamma \cdot d_i^{-\alpha} \quad (i \in \mathcal{N}), \tag{1}$$

where $\alpha$ denotes the path loss factor, $\gamma$ denotes an antenna related constant, and $d_i$ denotes the distance between transmitter and receiver of SU pair $i$. We suppose $\mathrm{SU}_i$ transmits data successful only when the received power at the SU's receiver is larger than $\mathrm{SU}_i$'s receiver sensitivity, $P_{Tx}$. Moreover, if interference is larger than a threshold of $P_{In}$ at the $\mathrm{SU}_i$'s receiver, the interference is non-negligible. Hence, from $\gamma \cdot (R_{Tx})^{-\alpha} \cdot P = P_{Tx}$, we represent the transmission range for a SU as $R_{Tx} = (\gamma P/P_{Tx})^{1/\alpha}$. Similarly, based on the interference threshold $P_{In}(P_{In} < P_{Tx})$, the interference range for a SU is $R_{In} = (\gamma P/P_{In})^{1/\alpha}$. It is obvious that $R_{In} > R_{Tx}$ since $P_{In} < P_{Tx}$. Typically, the interference range is 2 or 3 times of the transmission range [11], i.e., $\frac{R_{In}}{R_{Tx}} = 2$ or 3. The conflict relationship between SU pairs over the same band can be defined by the specified interference range. In addition, if we set the interference range properly, we can accurately transfer protocol to the physical model [12].

*2) Link Capacity/ Achievable Data Rate:* We use the ON/OFF model [13] to illustrate the active/inactive status of primary services in this paper. We assume that over band $k$, $\mathrm{PU}_k$ is "OFF" with probability $\beta_k$, it is obviously that $\mathrm{PU}_k$ is "ON" with probability $(1-\beta_k)$.

$\mathrm{SU}_i$ can access to available band $k$ with full transmission power $P$, while other SUs within $\mathrm{SU}_i$'s interference range keep silent. According to the Shannon-Hartley theorem, the capacity of SU $i \in \mathcal{N}$ over band $k \in \mathcal{M}$ is

$$c_i^{k,\mathrm{OFF}} = W^k \log_2\Big(1 + \frac{g_i P}{\sigma^2}\Big), \tag{2}$$

where $\sigma^2$ represents the ambient Gaussian noise power at $\mathrm{SU}_i$'s receiver.

When band $k$ is not available, SUs have to reduce their transmission power to ensure that the entire interference is below the $P_{Tx}$ of $\mathrm{PU}_k$ [14]. Suppose that the averaged interference tolerance power sensitivity for a SU is $P_\triangle^k$ at $\mathrm{PU}_k$'s receiver. Let $\mathrm{SU}_i$ accessing to band $k$ transmits with power $P_i^{k,\mathrm{ON}}$. Then, we have $P_\triangle^k = P_i^{k,\mathrm{ON}} \cdot g_{ik} = P_i^{k,\mathrm{ON}} \cdot \gamma \cdot d_{ik}^{-\alpha}$, where $d_{ik}$ is the distance between $\mathrm{SU}_i$ and $\mathrm{PU}_k$. Thus, when $\mathrm{PU}_k$ is "ON", the capacity of $\mathrm{SU}_i$ over band $k$ is

$$\begin{aligned} c_i^{k,\mathrm{ON}} &= W^k \log_2\Big(1 + \frac{g_i P_i^{k,\mathrm{ON}}}{P^k \gamma d_{ik}^{-\alpha} + \sigma^2}\Big) && (3) \\ &= W^k \log_2\Big(1 + \frac{g_i P_\triangle^k \gamma^{-1} d_{ik}^{\alpha}}{P^k \gamma d_{ik}^{-\alpha} + \sigma^2}\Big), && (4) \end{aligned}$$

where $P^k$ is the transmission power of $\mathrm{PU}_k$, $k \in \mathcal{M}$, and $P^k \gamma d_{ik}^{-\alpha}$ is the $\mathrm{PU}_k$'s interference to $\mathrm{SU}_i$ over band $k$.

Therefore, the expected capacity of $\mathrm{SU}_i$ over band $k$ can be written as

$$c_i^k = \beta_k c_i^{k,\mathrm{OFF}} + (1-\beta_k) c_i^{k,\mathrm{ON}}. \tag{5}$$

## III. Centralized Optimization Formulation of Spectrum Trading

In this section, we first use conflict graph to describe the interferences relationship among SUs, then mathematically formulate the centralized optimization problem with the objective of maximizing PUs' revenue under multiple wireless transmission constraints.

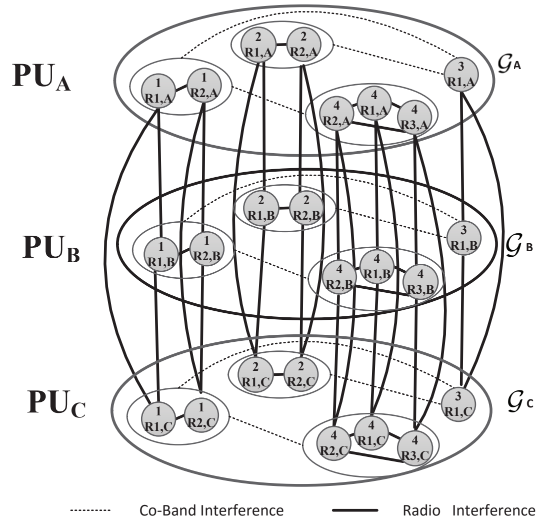


Fig. 2. Interference relationship represented by conflict graph in DMDST.

### A. Conflict Graph and Maximal Independent Sets

*1) Construction of Conflict Graph:* We employ conflict graph $\mathcal{G}(\mathcal{V},\mathcal{E})$ to characterize the interferences among SUs in DMDST. Each vertex represents to a SU using its corresponded radio to opportunistically accessing to certain band in $\mathcal{G}(\mathcal{V},\mathcal{E})$. There is interference if: (i) two different SUs are using the same band, the receiver of one SU transmission pair is in the interference range of the transmitter in the other SU pair; or (ii) two radios of the same SU pair transmit traffic over the same band; or (iii) a transceiver of a SU pair transmit over more than one band at the same time. Here, the first condition represents co-band interference, and the second and third condition represents the radio interface conflicts of SU itself. If there is interference between two vertices as shown in Figure 2, we connect them with an undirected edge. According to these conditions, we describe the impact of vertex $i_a \in \mathcal{V}$ on vertex $j_b \in \mathcal{V}$ in a given $\mathcal{G}(\mathcal{V},\mathcal{E})$ as follows,

$$\lambda_{i_a j_b} = \begin{cases} 1, & \text{if there is an edge between vertex } i_a \text{ and } j_b \\ 0, & \text{if there is no edge between vertex } i_a \text{ and } j_b, \end{cases} \tag{6}$$

where two vertices represents two SU-band pairs $i$, and $j$, using their corresponding radio $a$, and $b$, respectively.

*2) Maximal Independent Sets:* If a vertex set $\mathcal{I} \subseteq \mathcal{V}$ and the vertex $i_a \in \mathcal{I}$ satisfying $\sum_{j_b \in \mathcal{I}, i_a \neq j_b} \lambda_{i_a j_b} < 1$, the transmission at SU-band pair $i$ using transceiver $r$ will be successful even if all the other SU-band pairs in the set $\mathcal{I}$ are transmitting at the same time. If all $i_a \in \mathcal{I}$ satisfies the condition above, the spectrum frequency can be reused, and all the transmissions over these SU-band pairs in $\mathcal{I}$ can be active at the same time. Such a SU-band pair set $\mathcal{I}$ is called an independent set. If adding any one more SU-band pair into the independent set $\mathcal{I}$, it will turn to be a non-independent one, then $\mathcal{I}$ is defined as a maximal independent set (MIS) [15].

### B. The Formulation of Centralized Spectrum Trading Optimization

Let $\delta_{i_a}^k$ denotes status of SU $i \in \mathcal{N}$ using radio frequency $a \in \mathcal{R}$ to access band $k \in \mathcal{M}$. We use $\delta_{i_a}^k = 1$ denotes that SU$_i$ is transferring traffic over band $k$ by its transceiver $r$, otherwise 0. Given $\mathcal{G} = (\mathcal{V}, \mathcal{E})$ constructed from DMDST, assume we can list all MISs as $\mathscr{I} = \{\mathcal{I}_1, \mathcal{I}_2, \cdots, \mathcal{I}_q, \cdots, \mathcal{I}_Q\}$, where $Q$ is $|\mathscr{I}|$, and $\mathcal{I}_q \subseteq \mathcal{V}$ for $1 \leq q \leq Q$. Based on the definitions, assumptions and mathematical representations of interference relationship among SUs we make, the revenue maximization optimization problem in DMDST can be represented as follows.

$$\text{Maximize} \sum_{k \in \mathcal{M}} \sum_{i \in \mathcal{N}} \delta_{i_a}^k \tag{7}$$

s.t.:

$$\delta_{i_a}^k \in \{0, 1\}, \qquad (i \in \mathcal{N}, k \in \mathcal{M}, a \in \mathcal{R}), \tag{8}$$

$$\sum_{k \in \mathcal{M}, r \in \mathcal{R}} \delta_{i_a}^k \leq | R | \quad (i \in \mathcal{N}), \tag{9}$$

$$\delta_{i_a}^k \cdot \delta_{j_b}^k = 0, \qquad (i, j \in \mathcal{N}, k \in \mathcal{M}, a, b \in \mathcal{R}, (i_a, k) \in \mathcal{I}_u, (j_b, k) \in \mathcal{I}_v, \mathcal{I}_u, \mathcal{I}_v \in \mathscr{I} \text{ and } u \neq v) \tag{10}$$

where $\delta_{i_a}^k$ denotes optimization variable, since bidding value for all SUs is unit. Here, binary value $\delta_{i_a}^k$ describes the accessing status of SU$_i$ to band $k$ by transceiver $a$, Eq. (9) means the number of bands SU$_i$ accessing at same time can not be more than the number of transceivers that SU$_i$ has, and Eq. (13) presents the co-band interference constraint. This formulated optimization problem is a mixed-integer nonlinear programming (MINLP) problem, which has no classical optimal solution. Thus, we propose a new distributed matching scheme in the next section.

## IV. Dynamic Matching Based Distributed Spectrum Trading

In this section, we present some important definitions in DMDST matching. After that, we describe DMDST scheme how PUs' preferences evolves during the matching processing. At last but not the least, we prove the pairwise stability of the proposed DMDST.

### A. Definitions in Matching

*1) SUs' interferences in PU's observation:* In our work, a PU can only observe the interference relationship of SUs who propose to it and builds up its preferences based on its observation. Therefore we divide conflict graph $\mathcal{G}(\mathcal{V}, \mathcal{E})$ into $| \mathcal{M} |$ layers, where $\mathcal{G}^k(\mathcal{V}^k, \mathcal{E}^k)$ is the conflict graph over band $k \in \mathcal{M}$, $\mathcal{G}^k(\mathcal{V}^k, \mathcal{E}^k)$ is the conflict graph observed by PU$_k$. Since SUs can propose to all PUs in our model, every PU can observe the same conflict graph as others, namely $\mathcal{G}^A = \mathcal{G}^B = \mathcal{G}^B$ as shown in Figure 2.

Similar to the definition of $\mathcal{I}_u \in \mathcal{G}$ and $\mathscr{I} \subseteq \mathcal{G}$ in last section, we can define $\mathcal{I}_u^k \in \mathcal{G}^k$ and $\mathscr{I}^k \subseteq \mathcal{G}^k$, which describes the MISs observed by PU$_k$, and all the SUs in $\mathcal{I}_u^k$ can transmit simultaneously over band $k$.

*2) SUs' and PUs' Preference List:* The purpose for the SU$_i$ is to maximize its data transmission rate, i.e., Maximize $\sum_{k \in \mathcal{M}} \delta_{i_a}^k c_i^k$, subjected to $\delta_{i_a}^k \in \{0, 1\}$, and $\sum_{k \in \mathcal{M}} \delta_{i_a}^k \leq | \mathcal{R} |$, where $i \in \mathcal{N}, r \in \mathcal{R}$, and $c_i^k$ is defined in Sec. II-B. Hence we can construct a preference relation $\succ_i$, for $i \in \mathcal{N}$, as follows

$$k \succ_i l \Leftrightarrow c_i^k \succ_i c_i^l, \quad k, l \in \mathcal{M}. \tag{11}$$

Moreover, SU$_i$ can access over as many as $| \mathcal{R} |$ bands of PUs simultaneously.

On the other hand, for PU$_k$, the goal is to maximize its revenue. Since bidding price is unit in our model, PUs need to accept as many SUs as possible transmitting at the same time. Given $\mathcal{G}^k(\mathcal{V}^k, \mathcal{E}^k)$ observed by PU$_k$, we have

$$\text{Maximize} \sum_{i \in \mathcal{N}} \delta_{i_a}^k \tag{12}$$

s.t.:

$$\delta_{i_a}^k \in \{0, 1\}, \qquad (i \in \mathcal{N}, a \in \mathcal{M})$$

$$\sum \delta_{i_a}^k \leq 1, \qquad (i \in \mathcal{N}, a \in \mathcal{R})$$

$$\delta_{i_a}^k \cdot \delta_{j_b}^k = 0, \qquad (i, j \in \mathcal{N}, a \in \mathcal{R}, (i_a, k) \in \mathcal{I}_u, (j_b, k) \in \mathcal{I}_v, \mathcal{I}_u, \mathcal{I}_v \in \mathscr{I} \text{ and } u \neq v) \tag{13}$$

So, the preferences of PU$_k$ over two given SUs groups $\mathcal{I}_u^k$ and $\mathcal{I}_v^k$ can be represented as[1]

$$\mathcal{I}_u^k \succ_k \mathcal{I}_v^k \Leftrightarrow \sum_{i \in \mathcal{I}_u^k} i \succ \sum_{j \in \mathcal{I}_v^k} j. \tag{14}$$

*3) Individual Rationale and Pairwise Block:* Let $\mathbb{PL}(\cdot)$ denote the preference list. According to the preferences of SUs and PUs, we define

- For SU$_i$, $\forall i \in \mathcal{N}$, $k \in \mu(i)$, if SU$_i$ can access band $k$ owned by PU$_k$, and $\mu(i) = \Phi$, if SU$_i$ cannot access to any band. Moreover, $| \mu(i) | \leq | \mathcal{R} |$.
- For PU$_k$, $\forall k \in \mathcal{M}$, $\mu(k) = \mathcal{I}_u^k, \mathcal{I}_u^k \subseteq \mathscr{I}^k$, if PU$_k$ can accommodate every SU$_i$ over band $k$, where $i \in \mathcal{I}_u^k$; $\mu(k) = \Phi$, if all SUs are denied by PU$_k$ over band $k$.
- For PU$_k$ and SU$_i$, $\mu(i_a) = k$, if and only if $i \in \mu(k)$.

Based on those definitions in DMDST, we further define *individual rationale* [16] as:

***Definition 1:*** Given an user $x \in \mathcal{M} \cup \mathcal{N}$ (i.e., $x$ can either be PU or SU) and $\mathcal{S}$, a set of partners of user $x$, let $\Omega(\mathcal{S}, \mathbb{PL}(x))$ denotes user $x$'s most favorite subset of $\mathcal{S}$ according to $x$'s preference lists $\mathbb{PL}(x)$. A DMDST matching is defined as *individually rational* if and only if $\mu(x) = \Omega(\mu(x), \mathbb{PL}(x)), \forall x \in \mathcal{M} \cup \mathcal{N}$.

Furthermore, we define *pairwise block* as

***Definition 2:*** For matching result $\mu$, there is a SU-PU pair $(i, k)$,

[1]Here, we note that a PU has no preferences on which radio transceiver a SU using over its band. Since each SU can use only one radio to access to a same PU, we can use $i \in \mathcal{I}_u^k$ instead $i_a \in \mathcal{I}_u^k$ for specific $k$.

- $i \notin \mu(k)$, $i \in \Omega(\mu(k) \cup i, \mathbb{PL}(k))$;
- $k \neq \mu(i)$, $k = \Omega(\mu(i) \cup k, \mathbb{PL}(i))$.

If matching $\mu$ is *individually rational* and there is no *pairwise block* in $\mu$, then $\mu$ is ***pairwise stable***.

### B. DMDST with Evolving Preferences

We propose the DMDST matching procedure with PUs' evolving preferences in this subsection. The proposed DMDST matching process can be carried out in two phases and five steps, which is shown in details as follows.

*1)* ***Phase I:*** *Tentative Matching with PUs' Currently Observed MISs:* There are four steps in *Phase I*: (i) preparing preference lists, (ii) SUs' bids proposing, (iii) PUs' tentative matching with SUs (i.e., accessing/rejecting), and (iv) PUs' preferences evolving.

First of all, all PUs and SUs will initiate the procedure by preparing their preference lists. The $\text{SU}_i$ constructs its preference list $\mathbb{PL}(i)$ according to (11). Since no SU submits bids to $\text{PU}_k$ yet, $\text{PU}_i$ constructs the conflict graph $\mathcal{G}^k$ based on the *priori* information of the SUs within its coverage, and lists its preferences $\mathbb{PL}(k)$ according to (14). Notice that for PU, there is no preference on which radio transceiver of SU using to transmit, so in $\mathcal{G}^k$, each $\text{SU}_i$ can be considered as a group, i.e., $\text{SU}_i$ is in $\text{SU}_j$ range, then each radio of these two SUs interferes with each other.

Thus, having $\mathbb{PL}(i)$, $\text{SU}_i$ proposes to the top PU of $\mathbb{PL}(i)$ in this round. It is noted that all the SUs propose to the PUs simultaneously and a SU can propose to as many as $\mid R \mid$ PUs at a time.

After receiving the bids from SUs, $\text{PU}_k$ updates its $\mathcal{G}^k$, which includes the SUs bidding for $\text{PU}_k$ for the 1st round, and includes the already accepted SUs and SUs newly bidding for $\text{PU}_k$ from the 2nd round until the current round. $\text{PU}_k$ will tentatively access/match with the SUs in $\mathcal{I}_u^k$, where $\mathcal{I}_u^k = \underset{\mathcal{I}_u^k \in \mathcal{G}^k}{\operatorname{argmax}} \Big( \sum_{i \in \mathcal{I}_u^k} i \Big)$, and reject the SUs not in $\mathcal{I}_u^k$ based on the updated $\mathcal{G}^k$, .

After that, $\text{PU}_k$ evolves its preference list $\mathbb{PL}(k)$ based on the accepted $\mathcal{I}_u^k$. $\text{PU}_k$ puts MISs/SUs which do not interfere with $\mathcal{I}_u^k$ in higher priorities, and MISs/SUs which interfere with $\mathcal{I}_u^k$ in lower priorities. Then, the process goes back to *Step 2*, where SUs start to proposed to PUs which they do not propose yet by the order of preference list, as long as there are vacant transceiver of SUs available.

The iterations continues until all transceiver of SUs are occupied or SUs have proposed to all PUs in preference lists..

*2)* ***Phase II:*** *Block-Proof Matching with SUs' Swapping:* In *Phase II*, $\text{SU}_i$ will propose again to the $\text{PU}_k$, which $\text{SU}_i$ prefers to any of its current matching $k'$, $k' \in \mu(i)$, i.e., $k \succ_i k'$. Then, compared with $\text{PU}_k$'s current revenue, $\text{PU}_k$ will check if accessing $\text{SU}_i$ can make itself receive more monetary gain. If yes, $\text{SU}_i$ will be swapped to $\text{PU}_k$, and $\text{PU}_k$ will update MIS including $\text{SU}_i$, evict SUs who interfere with $\text{SU}_i$, and evolve $\text{PU}_k$'s preferences. The evicted SUs will repeat the same procedure until no more swapping is needed.

Note that PUs just need to make decision of accepting/rejecting the SUs' swaps based on PUs' preferences, and there is no requirement for PUs to share information, or communicate with another PUs. That keeps the distributed feature of the proposed DMDST.

*3) Pairwise Stability of DMDST:* The matching result of the proposed Algorithm 1 is pairwise stable.

*Proof:* It is proved by contradiction. Suppose the final matching result is not pairwise stable, i.e, $\exists k', \exists i, k' \notin \mu(i)$, $k' \in \Omega(\mu(i) \cup k', \mathbb{PL}(i))$, and $i \notin \mu(k')$, $i \in \Omega(\mu(k') \cup i, \mathbb{PL}(k'))$. In other word, $\mu(k') \neq \Omega(\mu(k') \cup i, \mathbb{PL}(k'))$ and $\mu(i) \neq \Omega(\mu(i) \cup k', \mathbb{PL}(i))$. It means that $\text{SU}_i$ prefers to join another band of $\text{PU}_{k'}$ rather than its current matching results $\text{PU}_k$. Moreover, $\text{PU}_{k'}$ would like to accept it since it can generate more revenue from accepting $\text{SU}_i$. If the pairwise block exist, the algorithm will transfer the element of block in *Phase II*. Then, after *Phase II*, $i \in \mu(k')$, $\mu(k') = \Omega(\mu(k'), \mathbb{PL}(k'))$, and $k' = \mu(i), \mu(i) = \Omega(\mu(i), PL(i))$. Hence, the result of DMDST is pairwise stable. ■

## V. Performance Evaluation

We consider a network consisting of 15 SUs and 5 PUs randomly deployed in a 1000x1000 m$^2$ area. The noise power $\sigma^2$ is $10^{-10}$ W, the path loss factor $\alpha$ = 4, the antenna parameter $\gamma$ = 3.90625, the receiver sensitivity $P_T$ = $100\sigma^2$ = $10^{-8}$ W and the interference threshold $P_T$ = $6.25 \times 10^{-10}$ W. For illustrative purposes, we assume all the bands have different bandwidths, which are randomly selected from 10 MHz to 15MHz. We also assume transmission power of PU, SU and SU when PU coming back are $20 \times 10^{-8}$ W, $15 \times 10^{-8}$ W and $7 \times 10^{-8}$ W. The distance between transmitter and receiver of SU is 20m, and the distances between PU and SU are randomly from 1m to 60m. The data transmission rates of SUs can be calculate by Eq. (5), where the probability values of PUs' coming back are randomly selected from 0 to 1. For simplicity's sake, every SU bid value is \$1, $Z$ = 10000 as a large enough number for the MISs. Here, by employing $Z$ MISs found in multi-dimensional $\mathcal{G}$, centralized optimization results can be obtained by commercial solvers such as CPLEX [17], and serve as a benchmark for the performance comparison.

First, we compare PUs' total revenue under DMDST and Gale-Shapley(GS) algorithm in Figure 3. It is obviously to see that GS has the worst performance, since GS has no consideration about frequency reuse, which means each PUs only allows one SU to trade the spectrum at the same time. Taking frequency reuse and multiple radio into account, the revenue of total network for DMDST increases as number of SUs increases, and is close to the optimal solution thanks to MIS and dynamic matching with evolving preferences list of PUs. Then we have some insights on the aggregated SU network throughput in Figure 4. We compare the performance under tow modes, "ON" and "OFF", respectively. "ON" mode means SUs keep working but decrease transmission power when PUs come back, while "OFF" mode means SUs will keep silence when PUs using their band. It is shown that

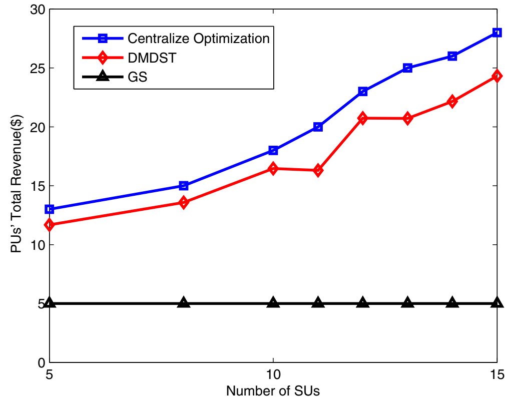


Fig. 3. Total Revenue of PUs, $M$=5.

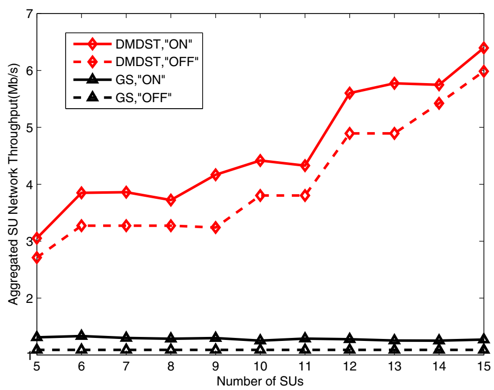


Fig. 4. Arregated SU Network Throughput, $M$=5.

the performance of "ON" mode is better than "OFF" mode for both two algorithms since SUs keep transmitting data when PUs come back on "ON" mode; and the performance of DMDST is also superior than the results of GS under both two modes, since GS algorithm only allow one SU to use each PU's spectrum. The reason for fluctuation of performance results under DMDST is that, the goal of DMDST is to maximize the monetary gain of all PUs, but not the total network throughput. For example, when more SUs attend the network, PUs will choose the MIS which has more number of SUs to get more monetary gain, even though the total network throughout of this MIS may be lower than other MISs.

## VI. Conclusion

In this paper, we have proposed a novel dynamic matching based distributed spectrum trading (DMDST), which jointly considers spectrum reuse and the features of MRMC transmissions. We have introduced conflict graph to characterize the interference relationship of SUs. Based on the constructed conflict graph, we have formulated the spectrum trading optimization with the objective of PUs' revenue maximization. Since this problem is MINLP and NP-hard to solve, we have developed the DMDST algorithm using dynamic matching with evolving preferences, and proven its pairwise stability. Through simulations, we have shown that the proposed algorithm outperforms other distributed algorithms, yields sub-optimal solutions, and is effective in improving PUs' revenues and aggregated SU network throughput.

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