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M^3-STEP: Matching Based Multi-Radio Multi-Channel Spectrum Trading with Evolving Preferences

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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 still have to face many practical but challenging issues, such as the new infrastructure deployment, the extra control overhead, and the scalability issues. To address those issues, in this paper, we propose a novel matching based multi-radio multi-channel spectrum trading (M^3-STEP) scheme in cognitive radio (CR) networks. We employ conflict graph to characterize the 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 M^3-STEP algorithms based on conflict graph observed by PUs, solve the problem via dynamic matching with evolving preferences, and prove its pairwise stability. Simulation results show that the proposed M^3-STEP algorithm achieves close to optimal performance 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

With the dense development of wireless devices, the wireless applications and services have experienced explosive growth during the last decade. Such explosion, however, has raised many challenges to the filed of wireless communications, of which the most urgent thing is to dig more radio spectrum [1]–[6]. Nevertheless, there is an observation that even in the most crowded region of cities, the licensed spectrum bands have not been fully utilized [1], [2], [7]. In this context, cognitive radio (CR) offers an alternative to easing the crowded spectrum by allowing the secondary users (SUs) to access the vacant spectrum in either temporal or spatial domain. In this way, the utilization efficiency of the limited spectrum could be further improved [1], [6]. Due to the high economic values of spectrum, cognitive radio technology and opportunistic spectrum accessing have initiated the spectrum market [2]–[4], where 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 [5], [8], [9]

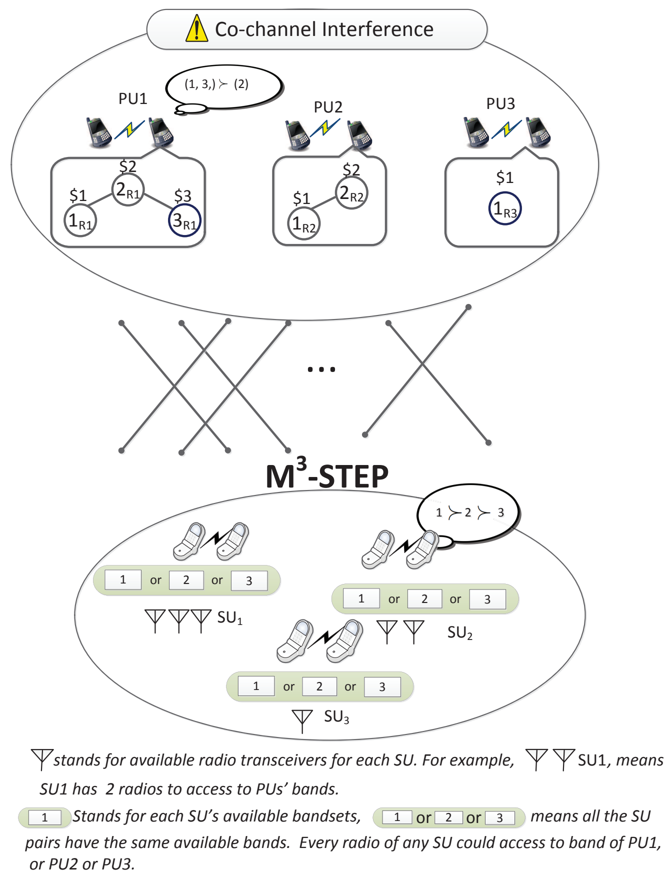

Fig. 1. Network Architecture for M^3-STEP in CRNs.

Unlike common commodities, spectrum has a very special feature, i.e., its spatial reusability, which has promoted many research works on the centralized design of spectrum trading [9]–[11]. Although the centralized spectrum trading design takes spectrum reuse into account and guarantees economic properties, it may not capture instantaneous accessing opportunities, and have scalability issues, when the network size of SUs increases. When the network grows too fast, i.e, there are too many users involved in the spectrum trading, the centralized system may need advanced processor to handle it. Since the explosive growth of wireless devices,

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the upgrade of centralized processor cost lots of unexpected money and resources. Beyond the centralized spectrum trading design, there are some interesting distributed spectrum trading schemes, which offer better network scalability than the centralized one. Beyond that, distributed designs can also provide quick responses to some emergency situations, e.g., unfortunate attacks of 9/11, Hurricane Katrina, etc., where the centralized infrastructure deployment may be destroyed. Therefore, the distributed spectrum trading algorithm is in need. However, most existing distributed spectrum trading have little concern of spatial reuse, which might lead to not only monetary loss of PUs, but also missing valuable spectrum accessing opportunities for SUs, which may limit the improvement efficiency of spectrum utilization. Besides, most existing distributed spectrum trading designs target at single-radio single-channel scenario, and there is a lack of distributed spectrum trading schemes in multi-radio multi-channel (MRMC) cognitive radio networks (CRNs)..

To address the above issues, in this paper, we propose a novel matching based multi-radio multi-channel spectrum trading (M^3-STEP) scheme, which jointly considers spectrum reuse and MRMC features, and allows spectrum trading between PUs and SUs in a distributed manner in MRMC CRNs. In M^3-STEP, we employ dynamic matching to trade the spectrum with the objective of maximizing PUs' revenues. Different from traditional matching [12], [13], 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 M^3-STEP matching algorithm, prove its stability, and conduct performance evaluations. We find 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 Fig. 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 obtain feasible solutions in distributed manners, we exploit dynamic matching with preferences to propose a novel M^3-STEP scheme by jointly considering interference mitigation, spatial reuse, MRMC transmissions, and spectrum trading benefits in matching process. In M^3-STEP, 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 these SUs have no mutual interferences. A PU lists its preferences over SUs based on its observations of SUs' conflicts. Moreover, the preference lists of PUs evolve during the matching procedure [14]. In this paper, we model both PUs' and SUs' utility functions, develop a two-phase matching algorithm with evolving preferences of PUs, and prove its pairwise stability [15].
- Through extensive simulations, we show that the proposed M^3-STEP outperforms other distributed spectrum trading algorithms without considering frequency reuse in MRMC CRNs, and the feasible solutions obtained by the proposed algorithm are close to the optimal one in terms of the PUs' revenues and spectrum utilization improvement.

The rest of paper is organized as follows. In Section II, we review related work in CRN spectrum trading. Section III introduces the network model and related models in M^3-STEP. In Section IV, we formulate the centralized PUs' revenue maximization problem. In Section V, we develop the M^3-STEP algorithm and prove its stability. We evaluate the performance in Section VI, and draw conclusion remarks in Section VII.

II. Related Work

Prior work has investigated spectrum trading issues from different aspects. For example, Grandblaise et al. [5] generally describe the potential scenarios and introduce some microeconomics inspired spectrum trading mechanisms, and in [16], Sengupta and Chatterjee propose an economic framework for opportunistic spectrum access to guide the design of dynamic spectrum allocation algorithms as well as service pricing mechanisms. Zhou et al. in [9] propose an incentive compatible spectrum trading mechanism where each SU has only one radio. In [17], Zhou and Zheng have extended their work in [9], and presented a truthful double spectrum auction, called TRUST, where multiple PUs and SUs can trade bands according to their own demands. Given SUs equipped with multiple radios, Li et al. [10] study a per transmission link based spectrum trading in multi-hop cognitive cellular network, and present its economic-robustness. Pan et al. [11] further extended the design into session-based spectrum trading design, and investigated PUs' revenue maximization problem in MRMC cognitive radio networks (CRNs). Beyond spectrum trading design in a centralized way, distributed spectrum trading design has been extensively investigated in existing literature. For example, Xing et al. [18] 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, with each other to offer spectrum access to the SUs. Using models in game theory, Wang et al. [19], Duan et al. [20] and Zhang et al. [21] proposed to construct spectrum trading systems with desired properties, such as power efficiency, allocation fairness, Pareto efficiency and collusion resistance. Wang et al. proposed a new algorithm using game theory which can make PUs find SUs at relatively better locations, and also help the competing SUs maximize their own utilities by asking the reasonable prices [19]. In [20], the proposed scheme study SUs' optimal investment including spectrum leasing and sensing, and pricing

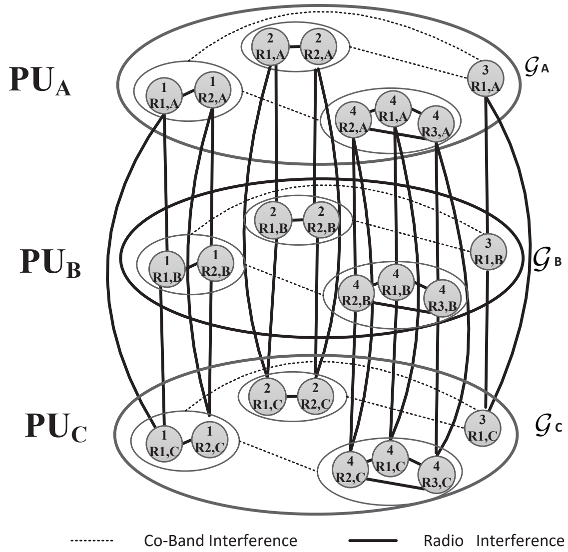


Fig. 2. Interference relationship represented by conflict graph.

strategies under PUs' spectrum supply uncertainty due to stochastic traffic. Zhang et al. proposed a novel cooperative cognitive radio framework which enables the primary user to involve secondary users as the cooperative relay and in return, the secondary users achieve the opportunity to access the wireless channel for their own data transmission [21]. Teng et al. used double auction mechanism which allows SUs to make decision based on their own interests to maximize the social welfare [22]. Zhang et al. and Gu et al. employed many-to-one/student-project matching to share the spectrum trying to maximize the social welfare in CR networks/LTE-Unlicensed systems, respectively [12], [13]. Moreover, Yang et al. proposed a prospect pricing mechanism under game theory, which jointly considers pricing strategy of SU and radio resource management to improve the utilization of radio resources in MRMC CRN [23]. However, there remains a lack of study to incorporate spatial reuse and dynamic matching in spectrum trading systems.

In this work, we are trying to bridge the gap between these two active research areas in MRMC CRNs. With the proposed spectrum trading system, we have a comprehensive study on the optimal spectrum trading problem considering multiple factors including interference relationship between SUs, different bidding values, evolving preference list, etc. Our work effectively extends the one-to-one matching spectrum trading into many-to-many matching mechanism for SUs and PUs, and makes those microeconomics inspired spectrum trading mechanisms practically applicable in MRMC CRNs.

III. Network Model

A. Network Configuration

As shown in Fig. 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

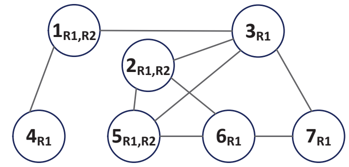


Fig. 3. A toy overall conflict graph observed by a PU.

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 the same as those at another SU in the network, i.e., every SU has 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 $i \neq j$.

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 the service of PU$_k$ is active. Suppose that the bidding values of SUs for opportunistic spectrum accessing are $\mathcal{B} = \{b_1, b_2, \cdots, b_N\}$. Thus, from the SU's perspective, considering it has several accessible radio interfaces, it would like to choose the bands over which it can achieve the maximum transmission rate; from the PU's perspective, considering spatial reuse, it would like to accommodate as many SUs as possible to receive the maximum revenues. For example, in Fig. 1, PU$_A$ observes interfere relationship among SU$_1$, SU$_2$ and SU$_3$, which try to access PU$_A$'s band at same time. The bid summation of SU$_1$ and SU$_3$ is larger than the bid of SU$_2$ (where \$1+\$3 > \$2), and SU$_1$ and SU$_3$ have no interference. The interference relationship is modeled by conflict graph, which we will discuss in details in Section IV.

B. Other Related Models in Spectrum Trading

1) SU's Transmission Range/Interference Range: SUs can use a certain band with full power if 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 [24], [25]

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

where α denotes the path loss factor, γ denotes an antenna related constant, and d_i denotes the distance between transmitter and receiver of SU pair i. We suppose SU$_i$ transmits data successful only when the received power at the SU's receiver is larger than SU$_i$'s receiver sensitivity, P_{Tx}. Moreover, if interference is larger than a threshold of P_{In} at the 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

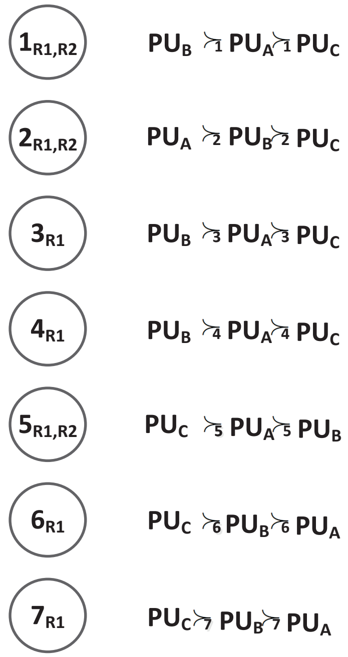


Fig. 4. SUs′ preference lists in M^3-STEP.

range is 2 or 3 times of the transmission range [25]–[30], 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 [31].

2) Link Capacity/Achievable Data Rate: We use the ON/OFF model [32] to illustrate the active/inactive status of primary services in this paper. We assume that over band k, PU$_k$ is "OFF" with probability β_k, and it is obviously that PU$_k$ is "ON" with probability $(1-\beta_k)$.

SU$_i$ can access to available band k with full transmission power P, while other SUs within 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

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

where σ^2 represents the ambient Gaussian noise power at SU$_i$'s receiver.

When band k is not available, SUs have to reduce their transmission powers to ensure that the entire interference is below the P_{Tx} of PU$_k$ [2]. Suppose that the averaged interference tolerance power sensitivity for a SU is $P_\triangle^k$ at PU$_k$'s receiver. Let SU$_i$ accessing band k transmit with power $P_i^{k,\text{ON}}$. Then, we have $P_\triangle^k = P_i^{k,\text{ON}} \cdot g_{ik} = P_i^{k,\text{ON}} \cdot \gamma \cdot d_{ik}^{-\alpha}$, where d_{ik} is the distance between SU$_i$ and PU$_k$. Thus, when PU$_k$ is "ON", the capacity of SU$_i$ over band k is

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

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

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

$$c_i^k = \beta_k c_i^{k,\text{OFF}} + (1-\beta_k) c_i^{k,\text{ON}}. \tag{4}$$

IV. Centralized Optimization Formulation of Spectrum Trading

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

A. Conflict Graph and Maximal Independent Set

1) Construction of Conflict Graph: We employ conflict graph $\mathcal{G}(\mathcal{V},\mathcal{E})$ to characterize the interferences among SUs in M^3-STEP [28], [29], [33], [34]. Each vertex represents a SU using its corresponding radio to opportunistically access to a 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 of the other SU pair; (ii) two radios of the same SU pair transmit traffic over the same band; or (iii) a transceiver of a SU pair transmits over more than one band at the same time. Here, the first condition represents co-band interference, and the second and third conditions represent the radio interface conflicts of SU itself. If there is interference between two vertices as shown in Fig. 2, we connect them with an undirected edge.

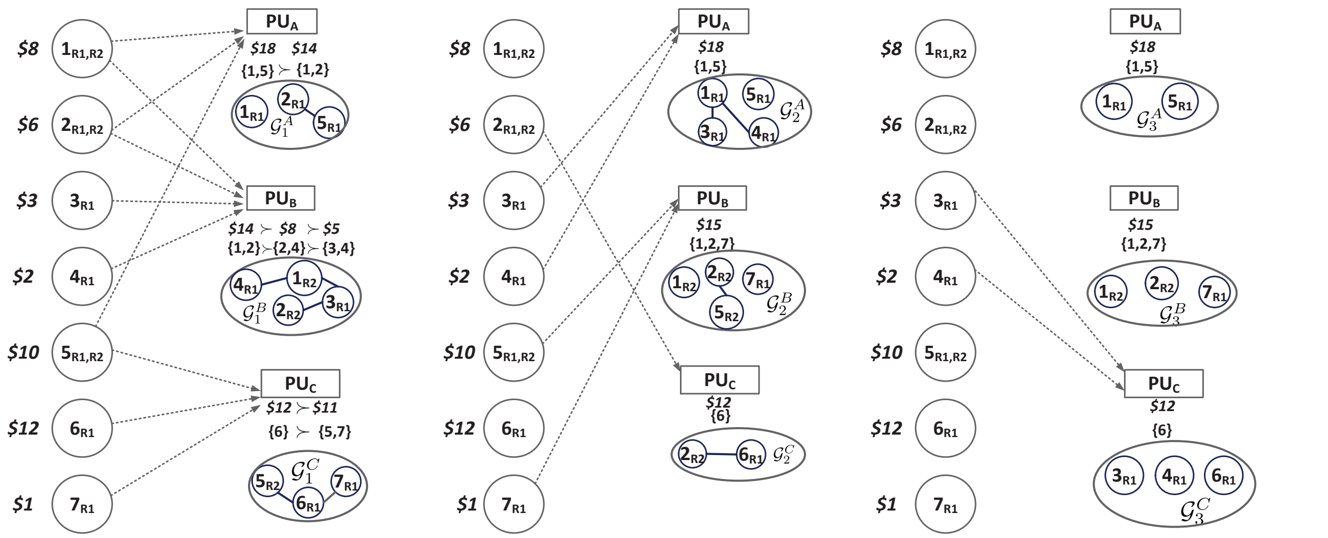
According to these conditions, we describe the impact of vertex $i_r \in \mathcal{V}$ on vertex $j_s \in \mathcal{V}$ in a given $\mathcal{G}(\mathcal{V},\mathcal{E})$ as follows,

$$\lambda_{i_r j_s} = \begin{cases} 1, \text{ if there is an edge between vertex } i_r \text{ and } j_s \\ 0, \text{ if there is no edge between vertex } i_r \text{ and } j_s, \end{cases} \tag{5}$$

where two vertices represents two SU-band pairs i, and j, using their corresponding radio r, and s, respectively.

To be more specific, in Fig. 2, vertices (1, R1, A) and (3, R1, A) stands for the radio 1 of SU$_1$ and radio 1 of SU $_3$ observed by PU$_A$. They are connected by an edge, which corresponds to the channel interferences we discussed previously. Similarly, connected vertices (1, R1, A) and (1, R2, A) means radio 1 of SU$_1$ and radio 2 of SU$_1$ cannot both transmit traffic over spectrum of PU$_A$ simultaneously, since the radio interference. Connected vertices (1, R1, A) and (1, R1, B) stands for that a same transceiver of one SU (here is SU$_1$) cannot transmits over more than one band at same time.

2) Maximal Independent Sets: If a vertex set $\mathcal{I} \subseteq \mathcal{V}$ and the vertex $i_r \in \mathcal{I}$ satisfy $\sum_{j_s \in \mathcal{I}, i_r \neq j_s} \lambda_{i_r j_s} < 1$, 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 $i_r \in \mathcal{I}$ satisfy 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 additional 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) [28].



(a) 1st round proposal.

(b) 2nd round proposal.

(c) 3rd round proposal.

Fig. 5. **Phase I:** Tentative matching with PUs' currently observed MISs.

B. The Formulation of Centralized Spectrum Trading Optimization

Let $\delta_{i_r}^k$ denote the status of SU $i \in \mathcal{N}$ using radio frequency $a \in \mathcal{R}$ to access band $k \in \mathcal{M}$. We use $\delta_{i_r}^k$ = 1 to denote that SU_i is transferring traffic over band k by its transceiver r, and 0 otherwise. Given $\mathcal{G} = (\mathcal{V}, \mathcal{E})$ constructed from M^3-STEP, 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 the interference relationship among SUs we make, the revenue maximization optimization problem in M^3-STEP can be represented as follows.

$$\text{Maximize} \sum_{k\in\mathcal{M}} \sum_{i\in\mathcal{N}} \sum_{r\in\mathcal{R}} \delta_{i_r}^k b_i \tag{6}$$

s.t.:

$$\delta_{i_r}^k \in \{0,1\}, \quad \forall i \in \mathcal{N}, k \in \mathcal{M}, r \in \mathcal{R}, \tag{7}$$

$$\sum_{r\in R} \delta_{i_r}^k \leq 1 \qquad \forall i \in \mathcal{N}, \tag{8}$$

$$\sum_{k\in\mathcal{M}} \sum_{r\in\mathcal{R}} \delta_{i_r}^k \leq\mid R \mid \quad \forall i \in \mathcal{N}, \tag{9}$$

$$\delta_{i_r}^k \cdot \delta_{j_s}^k = 0, \forall i, j \in \mathcal{N}, k \in \mathcal{M}, r, s \in \mathcal{R}, (i_r, k) \in \mathcal{I}_u, \\ (j_s, k) \in \mathcal{I}_u, i \neq j. \tag{10}$$

where binary value $\delta_{i_r}^k$ describes the access status of SU_i to band k by transceiver r, Eq. (8) indicates that SU_i cannot use more than one radio to access band k, Eq. (9) means the number of bands SU_i can access at the same time cannot be larger than the number of radios that SU_i has, and Eq. (10) represents the co-band interference constraint. This formulated optimization problem is a mixed-integer nonlinear programming (MINLP) problem, which is NP-Complete to solve. Due to the NP-Completeness of the problem and no existence of a centralized entity, we propose a distributed matching based spectrum trading scheme in the following section.

V. Dynamic Matching Based Distributed Spectrum Trading

In this section, we first present some important definitions in M^3-STEP matching. Next, we describe M^3-STEP scheme how PUs' preferences evolves during the matching processing. Last, we prove the pairwise stability of the proposed M^3-STEP.

In our work, a PU can only build up the interference relationship of SUs who propose to it in the current round. Every PU's observed conflict graphs in the current round are the subsets of conflict graph from god view, which contains all SUs. We divide the conflict graph from god view $\mathcal{G}(\mathcal{V}, \mathcal{E})$ into $\mid \mathcal{M} \mid$ layers, where $\mathcal{G}^k(\mathcal{V}^k, \mathcal{E}^k)$ is the conflict graph over band $k \in \mathcal{M}$ as observed by PU_k in overall perspective. In the nth round, PU_k's conflict graph is $\mathcal{G}_n^k$. Namely, in Fig. 2, the $\mathcal{G}^A = \mathcal{G}^B = \mathcal{G}^C$, and $\mathcal{G}_n^A \subseteq \mathcal{G}^A$

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

1) SUs' and PUs' Preference Lists: The purpose for SU_i is to maximize its data transmission rate, i.e., Maximize $\sum_{k\in\mathcal{M}} \sum_{r\in\mathcal{R}} \delta_{i_r}^k c_i^k$ subject to $\delta_{i_r}^k \in \{0,1\}$ and $\sum_{k\in\mathcal{M}} \sum_{r\in\mathcal{R}} \delta_{i_r}^k \leq\mid \mathcal{R} \mid$, where $i \in \mathcal{N}, r \in \mathcal{R}$, and c_i^k is defined in Sec. III-B. Hence we can construct a preference relation $\succ_i$ for $i \in \mathcal{N}$ as follows

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

Moreover, SU_i can access over as many as $\mid \mathcal{R} \mid$ bands of PUs simultaneously.

On the other hand, for PU_k the goal is to maximize its revenue. Since bidding prices are different in our model, PUs need to accept SUs with the highest value combination which can transmit at the same time. Given $\mathcal{G}^k(\mathcal{V}^k, \mathcal{E}^k)$ observed by PU_k, we have

$$\text{Maximize} \sum_{i\in\mathcal{N}} \sum_{r\in\mathcal{R}} \delta_{i_r}^k b_i \tag{12}$$

$$
\begin{aligned}
&\text{s.t.:}\\
&\delta_{i_r}^k \in \{0,1\}, \qquad (i \in \mathcal{N}, k \in \mathcal{M}, r \in \mathcal{R})\\
&\sum_{r\in R} \delta_{i_r}^k \leq 1 \qquad (i \in \mathcal{N}, r \in \mathcal{R}),\\
&\delta_{i_r}^k \cdot \delta_{j_s}^k = 0, \qquad (i,j \in \mathcal{N}, r,s \in \mathcal{R}, (i_r,k) \in \mathcal{I}_u,\\
&\qquad (j_s,k) \in \mathcal{I}_v, \mathcal{I}_u, \mathcal{I}_v \in \mathscr{I} \text{ and } u \neq v)
\end{aligned} \tag{13}
$$

Therefore, the preferences of PU_k over two given SU groups $\mathcal{I}_u^k$ and $\mathcal{I}_v^k$ can be represented as

$$
\mathcal{I}_u^k \succeq_k \mathcal{I}_v^k \Leftrightarrow \sum_{i_r \in \mathcal{I}_u^k} \sum_{r\in\mathcal{R}} \delta_{i_r}^k b_i \geq_k \sum_{j_s \in \mathcal{I}_v^k} \sum_{s\in\mathcal{R}} \delta_{j_s}^k b_j. \tag{14}
$$

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

- For any SU_i, $k \in \mu(i)$ if SU_i can access band k owned by PU_k, and $\mu(i) = \Phi$ if SU_i cannot access any band. Moreover, $\mid \mu(i) \mid \leq \mid \mathcal{R} \mid$.
- For any PU_k, $\mu(k) = \mathcal{I}_u^k, \mathcal{I}_u^k \subseteq \mathscr{I}^k$ if PU_k can accommodate every SU_i where $i \in \mathcal{I}_u^k$ over band k, and $\mu(k) = \Phi$ if all SUs are denied by PU_k over band k.
- For PU_k and SU_i, $\mu(i_r) = k$ if and only if $i \in \mu(k)$.

Based on these definitions in M[3]-STEP, we further define *individual rationale* [15] as:

***Definition** 1:* Given a 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 $\Omega(\mathcal{S}, \mathbb{PL}(x))$ denote user x's most favorite subset of $\mathcal{S}$ according to x's preference lists $\mathbb{PL}(x)$. A M[3]-STEP 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 μ, there is a SU-PU pair (i,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 μ is *individually rational* and there is no *pairwise block* in μ, then μ is ***pairwise stable***.

A. M[3]-STEP with Evolving Preferences

We propose the M[3]-STEP matching procedure with PUs' evolving preferences in this subsection. The proposed M[3]-STEP matching process can be carried out in two phases and five STEPs, which are 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. SU_i constructs its preference list $\mathbb{PL}(i)$ according to (11). Since no SU has submitted its bid to PU_k yet, PU_i constructs the conflict graph $\mathcal{G}^k$ based on the *a priori* information of the SUs within its coverage and lists its preferences $\mathbb{PL}(k)$ according to (14). Notice that for PUs, there is no preference on which radio transceiver of SUs used for transmitting. Therefore, in $\mathcal{G}^k$, each SU_i can be considered as a group, i.e., if SU_i is in SU_j range, then each radio of these two SUs interferes with each other. Thus, having $\mathbb{PL}(i)$, SU_i proposes to the top PU of $\mathbb{PL}(i)$ in this round. Note 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, PU_k updates its $\mathcal{G}^k$, which includes the SUs bidding for PU_k for the 1st round, and includes the already accepted SUs and SUs newly bidding

Algorithm 1 M[3]-STEP Phase I: Tentative Matching with PUs' Currently Observed MISs

Input Preference lists $\mathbb{PL}$, conflict graphs $\{\delta_{i_r}^k\}$, $\forall i \in \mathcal{N}, \forall k \in \mathcal{M}, \forall r \in \mathcal{R}$.
Output Matching result μ.
1. Initialization
$\forall k \in \mathcal{M}, \mu(k) = \emptyset$, the preference list of k, $\mathbb{PL}(k)$=$\mathscr{I}$.
$\forall i \in \mathcal{N}, \forall r \in \mathcal{R}, \mu(i_r) \in \mu(i), \mu(i_r) = i_r$, the preference list of i, $\mathbb{PL}(i)$=$\mathcal{M}$
$\mathbb{PO}(k)$ is the current proposer for k
$\mathbb{PO}(i)$ is the PUs that the SU i proposed in the current round.
2. SUs propose to PUs
for all $i \in \mathcal{N}$ **do**
  if $|\mathbb{PO}(i)| \leq |R|$ **then**
    SU i proposes to PU $k^* \in \mathbb{PL}(i)$,$\forall k' \in \mathbb{PL}(i)$, $k^* \succ_i k'$
    $\mathbb{PL}(i)$=$\mathbb{PL}(i) \backslash \{k^*\}$
    $k^* \in \mathbb{PO}(i)$
  end if
end for
3. PUs make decisions;
for all $k \in \mathcal{M}$ **do**
  Select a subset of non-interfering SU $O \subseteq \mathbb{PO}(k)$, $\forall i,j \in O$, $\delta_i^k \cdot \delta_{j_s}^k = 0$, $\sum_{i \in O} \delta_i^k b_i$ is maximized
  if $\exists O^*$ and O', $\sum_{i^* \in O^*} \delta_{i^*}^k b_{i^*}$ and $\sum_{i\prime \in O'} \delta_{i'}^k b_{i'}$ are both maximized **then**
    $\forall i^* \in O^* \cup \mu(k), i^* \in \mathcal{I}_u^k$
    $\forall i' \in O' \cup \mu(k)$,$i' \in \mathcal{I}_v^k$
    if $\forall j^* \in \mathcal{I}_u^k, \forall j' \in \mathcal{I}_v^k$,$\sum \delta_{j^*} b_{j^*}^k > \sum \delta_{j'}^k b_{j'}$ **then**
      $O = O^*$
    else
      $O = O'$
    end if
  end if
  $\mathbb{PL}(k)$=$\mathbb{PL}(k) \backslash \left\{ i^* | i^* \in \mathbb{PL}(k), \forall i' \in O, e_{i^*,i'}^k = 1 \right\}$
  $\mu(k) = \mu(k) \cup O$
  $\mu(i) = \mu(i) \cup k$
  $\mathbb{PO}(i) = \mathbb{PO}(i) \backslash \{k\}$
end for
if $\exists i \in \mathcal{N}, \exists r \in \mathcal{R}, \mu(i_r) = i_r$, and $\mathbb{PL}(i) \neq \emptyset$ **then**
  Go to STEP 2
else
  End of algorithm;
end if

for PU_k from the 2nd round until the current round. PU_k will tentatively access/match with the SUs in $\mathcal{I}_u^k$, where $\mathcal{I}_u^k = \underset{\mathcal{I}_u^k \in \mathcal{G}^k}{\operatorname{argmax}} \Big(\sum_{(i_r,k)\in\mathcal{I}_u^k} \sum_{r\in\mathcal{R}} \delta_{i_r}^k b_i \Big)$, and reject the SUs not in $\mathcal{I}_u^k$ based on the updated $\mathcal{G}^k$, .

After that, PU_k evolves its preference list $\mathbb{PL}(k)$ based on the accepted $\mathcal{I}_u^k$. 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 transceivers in SUs .

The iteration process continues until all transceiver of SUs are occupied or SUs have proposed to all PUs in preference lists. The algorithm of Phase I is summarized in Algorithm 1.

Phase I Example: Fig. 5 is an example for M^3-STEP with current MIS in *Phase I*. The conflict graph of each PU is based on Fig. 3. The SUs' preference lists are based on Fig. 4. As shown in Fig. 4, SU1, SU2 and SU5 have two radio transceivers, thus they can access to two PUs' bands at same time, and each SU has different bidding price.

In the first round, both SU_1 and SU_2 propose to 2 PUs, PU_A and PU_B simultaneously, and SU_5 proposes to PU_A and PU_C. Since other SUs only have one radio, it can just propose to one PU at a time. The SUs who propose to PU_A can be divided into two maximum independent sets, $\{SU_1,SU_5\}$ and $\{SU_1,SU_2\}$. According to the algorithm, PU_A chooses the set who has the highest revenue, which is \$18 of $\{SU_1,SU_5\}$. For the similar reason, PU_B accepts SU_1, SU_2 to receive the maximum revenue in this round and reject SU_3, SU_4. PU_C accepts SU_6 and rejects $\{SU_5,SU_7\}$.

In the second round, all PUs evict SUs which have impact on the accepted SUs in the first round. Then PUs evolve their preference lists to new ones. The rejected radio of SUs will propose to their next favorite PUs in preference list. Following the algorithm, SU_7 is accepted by PU_B since it does not interfere with $\{SU_1,SU_2\}$. SU_2, SU_3, SU_4 and SU_5 are still rejected by their proposed PUs since they are in conflict with previous accepted SUs.

Following the similar procedure, in the 3rd round, SU_2 and SU_5 already proposed to all PUs in their preference list, thus they will keep silence in this round. SU_3 and SU_4 are not accepted by any PUs yet and will propose to their last favorite PU in preference list. In our example, both SU_3 and SU_4 propose to PU_C and since they do not interference with SU_6, they are accepted by PU_C.

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

In other word, SU may need to swap several times to assure that the PUs which they prefer than its current matching PU are not willing to swap with them. While we cannot calculate the exactly round number we need in phase II, we can prove this procedure will converge. Since every PU has the same conflict graph in our network model, all the PUs' preference lists are the same. SUs which are in the MIS with more benefit revenue can be allocated to their most favorite PUs. On the other hand, the SUs which are evicted after swapping are always the SUs who have less bidding values or not in the MIS which have higher monetary gains. At last, this kind of SUs will be accepted by PUs which are in the lower rank of SUs' preference list. Thus, the phase two will converge at the end. This part is summarized in Algorithm 2.

Algorithm 2 M^3-STEP Phase II: Block-Proof Matching with SUs' Swapping.

Input Preference lists $\mathbb{PL}$, conflict graphs $\{\delta_{i_r}^k\}$, matching result from Phase I μ.
Output Update matching result μ.
if for i, $\exists k \succ \mu(i)$, according to $\mathbb{PL}(i)$, $i \in \mathcal{N}$ **then**
    i propose to k
    if $k \notin \mu(i)$, $k \in \Omega(\mu(i) \cup k, PL(i))$, and $i \notin \mu(k)$, $i \in \Omega(\mu(k) \cup i, \mathbb{PL}(k))$ **then**
        $\mu(k)^* = \mu(k)$
        $\mathcal{N}^* = \mu(k) \cup i$
        $\mu(k) = \Omega(\mu(k) \cup k, \mathbb{PL}(i))$
        $\mathcal{N}^* = \mathcal{N}^* \backslash \mu(k)$
    else
        Repeat ***Phase II***
    end if
end if

Note that PUs just need to make decisions of accepting/rejecting the SUs' swaps based on PUs' preferences, and there is no requirement for PUs to share information or communicate with other PUs. That keeps the distributed features of the proposed M^3-STEP. The matching result of the proposed Algorithm is pairwise stable.

Proof: It can be 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 SU_i prefers to join another band of $PU_{k'}$ rather than its current matching result PU_k. Moreover, $PU_{k'}$ would like to accept it since it can generate more revenue from accepting SU_i. If the pairwise block exists, 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 M^3-STEP is pairwise stable. ■

*3) **Computational Complexity** :* The complexity of the proposed M^3-STEP algorithm comes from two parts: (i) the complexity of finding MISs as PUs, and (ii) the complexity of matching between PUs and SUs. As we know, finding all MISs is NP-complete. Thus, we employ the greedy algorithm in [29] to find out a large number of MISs (e.g., the large number could be 2000) for approximation. The complexity of the greedy algorithm in [29] is $\mathcal{O}(M^4N^8X^4)$, here $X = max|\mathcal{R}|$, which indicates the maximum number of radio interfaces of

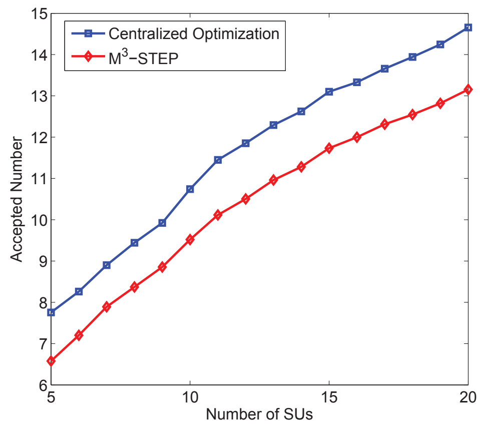


Fig. 6. Total accepted number of SUs' radios, $|M|$=3.

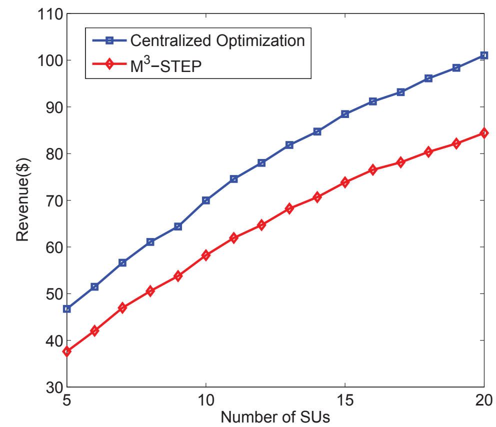


Fig. 8. Total revenues of PUs, $|M|$=3.

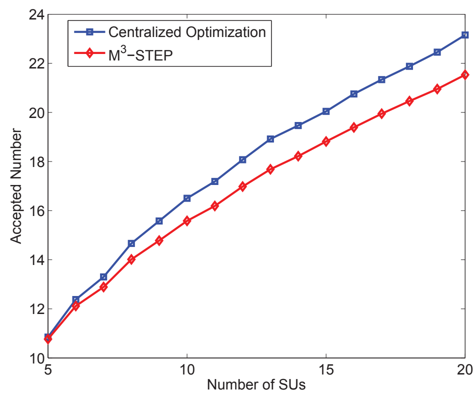


Fig. 7. Total accepted number of SUs' radios, $|M|$=5.

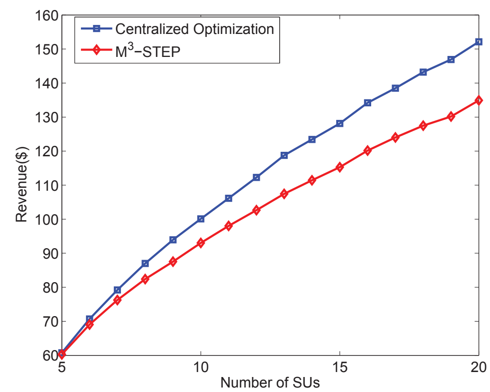


Fig. 9. Total revenues of PUs, $|M|$=5.

the SUs. As for the matching part, in the first phase, the matching complexity is determined by the total number of PUs and SUs, which is $\mathcal{O}(MN)$ [14], [35]–[37]. Similarly, in Phase II, even for the worst case (i.e., every PU and SU need swapping), the computational complexity of matching is $\mathcal{O}(MN)$. Thus, it can be easily inferred that the complexity of the matching is $\mathcal{O}(MN)$. Jointly considering the complexity of finding MISs and the matching, the overall complexity of the propose D-FROST algorithm is $\mathcal{O}(M^5N^9X^4)$.

VI. Performance Evaluation

A. Simulation Setup

We consider a CRN consisting of $|\mathcal{N}|$ = 20 SUs, where 20 nodes are randomly deployed in a 1000x1000 m^2 area. The noise power σ^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 comes back are 20×10^{-8} W, 15×10^{-8} W and 7×10^{-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. (4), where the probability values of PUs' coming back are randomly selected from 0 to 1. For simplicity, every SU bid price is randomly picked from [\$1,\$10], Z = 10000 as a large enough number for the MISs, and each SU has three radio transceivers to connect to channels of PUs.

B. Results and Analysis

First, we compare PUs' accepted numbers and total revenue under centralized optimization, M^3-STEP and GS (Gale Shapley) [35] algorithm in Fig. 6, Fig. 7, Fig. 8 and Fig. 9 with $|\mathcal{M}| = 3$ and 5, respectively. Here, by employing Z MISs found in multi-dimensional $\mathcal{G}$, centralized optimization results can be obtained by commercial solvers such as CPLEX [38], and serve as a benchmark for the performance comparison. It is not surprising to see that GS has the worst performance under $|\mathcal{M}| = 3$ and 5, since GS algorithm has no consideration about the frequency reuse. It means in GS, each PUs only allows one radio of SU to trade the spectrum at the same time. On the other hand, the revenue of the total network with M^3-STEP algorithm increases as the number of SUs increases, and is very close to the optimal solution both under $|\mathcal{M}| = 3$ and $|\mathcal{M}| = 5$, since M^3-STEP takes frequency reuse and multiple radio into account, which means allow more than one SUs trading on the same PU's spectrum simultaneously. Moreover, when $|\mathcal{M}| = 5$, both M^3-STEP and optimal results are overlap

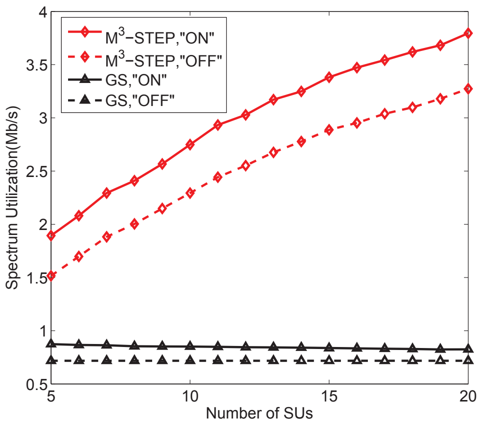


Fig. 10. Aggregated SU network throughput, $|M|$=3.

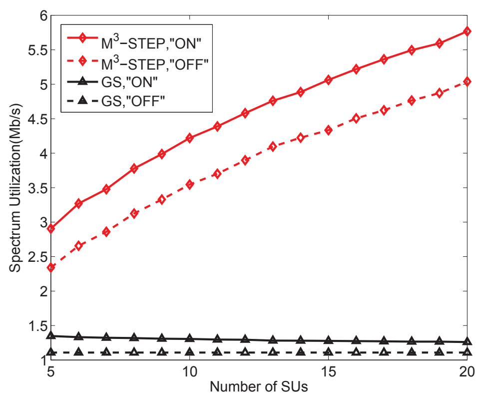


Fig. 11. Aggregated SU network throughput, $|M|$=5.

when the number of SUs is small enough in the matching.

Moreover, we have some insights on the aggregated SU network throughput in Fig. 10 and Fig. 11 under $|\mathcal{M}| = 3$ and $|\mathcal{M}| = 5$. We compare the performance under tow modes, "ON" and "OFF", respectively. "ON" mode means SUs keep working but decrease their transmission powers when PUs come back, while "OFF" mode means SUs will keep silence when PUs use their band. It is shown that 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. The performance of M^3-STEP is also superior to the results of GS under both two modes, since GS algorithm only allows one SU to use each PU's spectrum.

VII. Conclusion

In this paper, we have proposed a novel dynamic matching based distributed spectrum trading (M^3-STEP), which jointly considers spectrum reuse and the features of MRMC transmissions. We have introduced a 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 maximizing PUs' revenue. Since this problem is MINLP and NP-hard to solve, we have developed the M^3-STEP 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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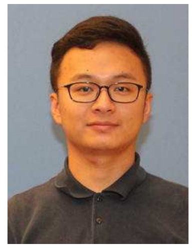

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