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Distributed Reciprocal-Selection-Based 'Win-Win' Cooperative Medium Access and its Stability Analysis

JIAO FENG[1,2], WEI LIANG[2], SOON XIN NG[2], AND LAJOS HANZO[2]

[1]School of Electric & Information Engineering, Nanjing University of Information Science & Technology, Nanjing 210044, China
[2]School of Electronics and Computer Science, University of Southampton, Southampton, SO17 1BJ, U.K.

Corresponding author: L. Hanzo (lh@ecs.soton.ac.uk)

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ABSTRACT In this paper, a distributed "Win-Win" reciprocal-selection-based medium access scheme (DWWRS-MAS) is designed for a cooperative spectrum leasing system hosting multiple licensed transmission pairs and multiple unlicensed transmission pairs. Based on the proposed DWWRS-MAS, the primary transmitter (PT) intends to lease its spectral resources to an appropriate secondary transmitter (ST) in exchange for cooperative transmission assistance for the sake of minimizing its transmit power and simultaneously satisfying its transmit rate requirement. The ST has an incentive to collaborate with the best PT for the sake of minimizing the ST's transmit power under the constraint of its QoS requirement, while simultaneously winning a transmission opportunity for its own traffic. Moreover, based on the matching theory and queueing theory, we analyze the algorithmic stability and the queueing stability of the cooperative spectrum leasing system exploiting our DWWRS-MAS, respectively. Simulation results demonstrate that our DWWRS-MAS is capable of providing both considerable energy savings and substantial rate improvements for the cooperative spectrum leasing system hosting multiple licensed transmission pairs and multiple unlicensed transmission pairs.

INDEX TERMS Cooperative medium access scheme, spectrum leasing, matching theory, queueing stability, reciprocal selection, cognitive radio network.

I. INTRODUCTION

1) BACKGROUND

Cognitive Radio (CR) techniques [1], [2] were proposed for efficiently exploiting the scarce spectral resources by enabling the unlicensed secondary users (SU) to access the spectrum originally licensed to the primary users (PU). The existing cognitive radio techniques may be classified into two categories, namely the common model[1] and the spectrum leasing model.[2] The benefits of CR techniques may be further improved by combining it with the cooperative communications techniques [2], [5], [6], where the relay node (RN) forwards the source's data for the sake of improving the throughput, reducing the energy consumption as well as extending the coverage area for the source.

2) STATE-OF-THE-ART

Numerous contributions have been developed based on the cooperative CR concept [7]–[10]. However, most of these existing contributions assumed that the relays agree to altruistically forward the data of the source node. This unconditional altruistic behaviour is unrealistic to expect from the mobile stations (MS). Bearing in mind the greedy behaviour of the mobile RNs, meritorious solutions were proposed in [11]–[14] based on cooperative spectrum leasing model, where the licensed PU intends to lease part of its spectral resources to the unlicensed SU in exchange for cooperative transmission assistance. The SU also has an incentive

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[1] According to the common model, the licensed PUs are capable of accessing the spectrum any time and are oblivious of the presence of unlicensed SUs. The SUs have to identify the the spectrum holes for the sake of conveying their data, provided that they do not substantially interfere with the transmissions of licensed users [3], [4].

[2] Under the spectrum leasing model, the licensed PUs are aware of the presence of unlicensed SUs and intend to lease part of their spectral resources to these unlicensed users in exchange for appropriate 'remuneration' [3], [4].

to forward data for the PU in exchange for a transmission opportunity for its own tele-traffic. Some of the existing contributions [13], [14] focused on the *contention between the SUs* in the cooperative spectrum leasing system (CSLS) hosting a single PU and multiple SUs. As a further advance, considering the scenario of having multiple PUs and a single SU, Elkourdi and Simeone [15] designed a meritorious framework for the sake of making a decision on the *contention between the multiple PUs*. However, the reciprocal selection between the PUs and SUs was not considered in the above contributions [13]–[15]. Based on the matching theory, Bayat *et al.* [16] and Namvar and Afghah [17] developed meritorious algorithms for finding the optimal matching between the PUs and SUs in order to maximize the utility of both the PUs and of the SUs. However, the authors of [16]–[19] aimed for maximizing either the *achievable transmit rate of PUs* [16]–[18] or the *system's total transmit rate* [19]. Finally, a delay-reduction techniques was conceived in [20].

3) CONTRIBUTIONS

Against this backcloth, we developed the following contributions.

- We first model a matching game based framework for capturing the details of the CSLS considered supporting *multiple* PUs and *multiple* SUs. Furthermore, based on the matching theory, a distributed 'win-win' reciprocal-selection-based medium access scheme (DWWRS-MAS) is developed for the sake of distributively producing the best cooperative pairs for the CSLS considered. Based on our DWWRS-MAS, each PU selects an appropriate SU as its best RN for minimizing its *transmit power* and for simultaneously improving its *transmit rate*. The SU intends to provide cooperative assistance for its best PU in order to minimize its *transmit power* and to simultaneously convey its own tele-traffic by using the licensed spectrum, whilst maintaining its target transmit rate.
- Moreover, we formally show that our DWWRS-MAS is capable of producing a stable matching by analysing the *algorithmic stability* of our DWWRS-MAS with the aid of matching theory.
- Finally, considering the bursty nature of the PU's traffic, we analyse the *queueing stability* of the CSLS exploiting the proposed DWWRS-MAS according to queueing theory.

The rest of this paper is organized as follows. Our system model is introduced in Section II, while our DWWRS-MAS is described in Section III. Section IV analyzes both the algorithmic stability and the queueing stability of the proposed DWWRS-MAS. In Section V, the attainable performance of our scheme is quantified. Finally, we conclude in Section VI.

II. SYSTEM MODEL

A. CONSTRUCTION AND ASSUMPTIONS

As seen in Fig 1, we consider a cooperative network having $\mathcal{I}$ primary transmission pairs (PTPs) in the set $\Theta_{PTP}(PT, PR) = \{\Theta_{PTP_i}(PT_i, PR_i)\}_{i=1}^{\mathcal{I}}$ and $\mathcal{M}$ secondary transmission pairs (STPs) in the set $\Theta_{STP}(ST, SR) = \{\Theta_{STP_m}(ST_m, SR_m)\}_{m=1}^{\mathcal{M}}$. The variables PT_i and PR_i denote the PT and PR of the i-th primary transmission pair (PTP) Θ_{PTP_i}, while ST_m and SR_m are the ST and the SR, which constitute the m-th secondary transmission pair (STP) Θ_{STP_m}. Each PTP is granted access to a unique spectral band, while the $\mathcal{M}$ STPs are not licensees. All the channels involved are assumed to undergo quasi-static Rayleigh fading. We consider the effects of the free-space pathloss that is modelled by $\rho = 1/d^{\eta}$, where d is the transmitter-to-receiver distance and η denotes the pathloss exponent. Both PTs and STs are assumed to be limited by the same maximum transmit power P_{max}.

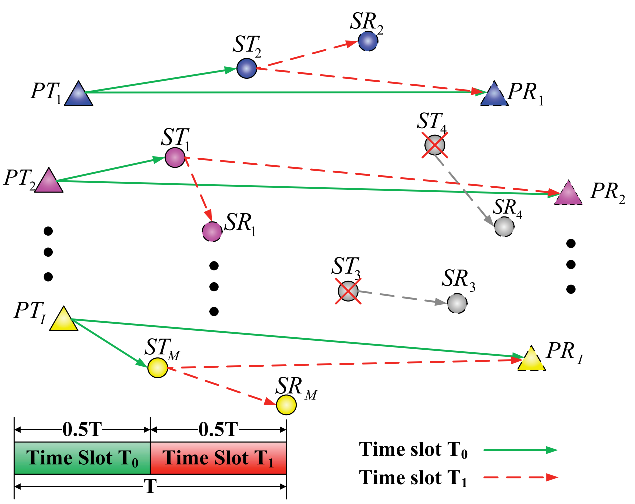


FIGURE 1. The system model.

Based on our CSLS, the original time period T allocated for the PTP may be divided into equally two time slots. When the PT is assisted by a specific ST, the PT relies on the first time slot to transmit data to both the PR and to the specific ST. During the second time slot, the specific ST ST_m first jointly encodes the data of the PT and of itself with the aid of superposition coding. Then ST_m conveys the superposition-coded data to the PR and SR during the second time slot. Successive Interference Cancellation (SIC) is invoked at the receiver for separating the PT's and ST's data. Then the PR combines both the direct transmission and the relayed transmission by using frame combining.

B. PT's OBJECTIVE FUNCTION

Each PT in our CSLS is encouraged to lease part of its spectral resources to a specific STP in exchange for cooperative transmission assistance for the sake of minimizing its transmit power as well as for improving its transmit rate. More explicitly, PTP Θ_{PTP_i} has a transmit rate requirement of $R_{PT_i}^{req} = \alpha C_{PT_i,PR_i}^{max}$ ($\alpha > 1$) which the ST should help achieve. In more detail, α is the ratio of the desired and affordable throughput termed as the PT's 'factor of greediness', while C_{PT_i,PR_i}^{max} is the maximum achievable rate of the corresponding

PT-to-PR (PP) link, which can be formulated as: $C^{max}_{PT_i,PR_i} = T\log_2(1+\frac{\rho_{PT_i,PR_i}|h_{PT_i,PR_i}|^2P_{max}}{P_N})$ where P_N is the power of the AWGN, while $|h_{PT_i,PR_i}|$ denotes the magnitude of the flat Rayleigh channel between PT_i and PR_i. Furthermore, ρ_{PT_i,PR_i} is the free-space pathloss between PT_i and PR_i. During the first time slot, the PT also intends to transmit its data at a minimum transmit power, which is capable of guaranteeing a successful cooperative transmission for the sake of minimizing the transmit power, whilst simultaneously improving the transmit rate. Hence, the objective function of the PT PT_i in our CSLS may be formulated as:

$$OF_{PT_i} = \min\sum_{m=1}^{\mathcal{M}}\{\xi_{ps}(i,m)\cdot P_{PT}(i,m)\}, \tag{1}$$

subject to

$$R_{PT_i}(i,m) = R^{req}_{PT_i}, \quad \forall i\in\{1,\ldots,\mathcal{I}\},\ \forall m\in\{1,\ldots,\mathcal{M}\}, \tag{2}$$

$$P_{PT}(i,m) \le P_{max}, \quad \forall i\in\{1,\ldots,\mathcal{I}\},\ \forall m\in\{1,\ldots,\mathcal{M}\}, \tag{3}$$

$$\sum_{m=1}^{\mathcal{M}}\xi_{ps}(i,m) \le 1, \quad \forall i\in\{1,\ldots,\mathcal{I}\}, \tag{4}$$

$$\sum_{i=1}^{\mathcal{I}}\xi_{ps}(i,m) \le 1, \quad \forall m\in\{1,\ldots,\mathcal{M}\}, \tag{5}$$

$$\xi_{ps}(i,m) \in \{0,1\}, \quad \forall i\in\{1,\ldots,\mathcal{I}\},\ \forall m\in\{1,\ldots,\mathcal{M}\}. \tag{6}$$

We refer to $\mathcal{O}(PT_i,ST_m)$ as a cooperative pair, when ST_m is granted access to the spectrum, which was originally licensed to PT_i for providing cooperative transmission assistance for PT_i and for simultaneously conveying its own data within the licensed spectrum. In a cooperative pair $\mathcal{O}(PT_i,ST_m)$, ST_m is referred to the "cooperative partner" of PT_i, namely we have $M^*(i) = m$. The PT_i of the cooperative pair $\mathcal{O}(PT_i,ST_m)$ is also termed as the "cooperative partner" of ST_m, namely we have $I^*(m) = i$. Therefore, $\xi_{ps}(i,m)$ is equal to 1 when PT_i and ST_m constitute a cooperative pair $\mathcal{O}(PT_i,ST_m)$. Otherwise, $\xi_{ps}(i,m)$ is set to 0. Eq (2) and Eq (3) formulate the transmit rate requirement of PT_i and the maximum transmit power constraint, respectively. Eq (4) ensures that only a single ST provides cooperative transmission assistance for PT_i. Moreover, Eq (5) ensures that ST_m has only a single cooperative partner. Based on the cooperative transmission assistance of ST_m, PT_i is capable of successfully conveying its data at a *minimum* transmit power and at an *increased* transmit rate of $R^{req}_{PT_i} = \alpha C^{max}_{PT_i,PR_i}$ $(\alpha > 1)$. If PT_i cannot acquire any cooperative transmission assistance, it directly transmits its data to PR_i.

C. ST's OBJECTIVE FUNCTION

Each ST has an incentive to forward data for its cooperative partner in exchange for accessing the PT's spectrum in order to convey its own traffic in our CSLS. Considering the greedy nature of ST, ST_m reserves a certain fraction of $R^{req}_{ST_m} = \beta C^{max}_{ST_m,SR_m}$ $(0 < \beta < 1)$ of the ST-to-SR (SS) channel's capacity for conveying its own tele-traffic, where β is the ST's 'factor of greediness' and $C^{max}_{ST_m,SR_m}$ is given by: $C^{max}_{ST_m,SR_m} = \frac{T}{2}\log_2(1+\frac{\rho_{ST_m,SR_m}|h_{ST_m,SR_m}|^2P_{max}}{P_N})$ while $|h_{ST_m,SR_m}|$ denotes the magnitude of the flat Rayleigh channel between ST_m as well as SR_m. Furthermore, ρ_{ST_m,SR_m} is the free-space pathloss between ST_m and SR_m. We refer to $P^S_{ST}(i,m)$ as the transmit power necessitated for achieving the target rate of ST_m, when PT_i is its cooperative partner. Furthermore, ST_m has to consume extra transmit power $P^P_{ST}(i,m)$ for helping PT_i achieve its target transmit rate $\alpha C^{max}_{PT_i,PR_i}$. We refer to $P_{ST}(i,m) = P^S_{ST}(i,m) + P^P_{ST}(i,m)$ as the total transmit power consumed by ST_m for achieving the target rate of both PT_i and itself. Considering the selfish nature of the STs, when multiple PTs intend to lease part of their spectral resource to the ST ST_m, ST_m may provide cooperative transmission assistance for the best PT for the sake of minimizing its total transmit power. Hence, the objective function of the ST in our system may be formulated as:

$$OF_{ST_m} = \min\sum_{i=1}^{\mathcal{I}}\{\xi_{ps}(i,m)\cdot P_{ST}(i,m)\}, \tag{7}$$

subject to

$$R_{ST_m}(i,m) = R^{req}_{ST_m}, \quad \forall i\in\{1,\ldots,\mathcal{I}\},\ \forall m\in\{1,\ldots,\mathcal{M}\}, \tag{8}$$

$$R_{PT_i}(i,m) = R^{req}_{PT_i}, \quad \forall i\in\{1,\ldots,\mathcal{I}\},\ \forall m\in\{1,\ldots,\mathcal{M}\}, \tag{9}$$

$$P_{ST}(i,m) \le P_{max}, \quad \forall i\in\{1,\ldots,\mathcal{I}\},\ \forall m\in\{1,\ldots,\mathcal{M}\}, \tag{10}$$

$$\sum_{i=1}^{\mathcal{I}}\xi_{ps}(i,m) \le 1, \quad \forall m\in\{1,\ldots,\mathcal{M}\}, \tag{11}$$

$$\sum_{m=1}^{\mathcal{M}}\xi_{ps}(i,m) \le 1, \quad \forall i\in\{1,\ldots,\mathcal{I}\}, \tag{12}$$

$$\xi_{ps}(i,m) \in \{0,1\} \quad \forall i\in\{1,\ldots,\mathcal{I}\},\quad \forall m\in\{1,\ldots,\mathcal{M}\}. \tag{13}$$

Eq (8) and Eq (10) formulate the transmit rate requirement of ST_m and the maximum transmit power constraint at ST.

III. DISTRIBUTED WW RECIPROCAL-SELECTION-BASED MEDIUM ACCESS SCHEME

Based on our CSLS introduced in Section II, in this section a DWWRS-MAS is designed for distributively selecting an appropriate cooperative matching pair.

A. MATCHING GAME FRAMEWORK

Based on the matching theory, the PTs and STs of our system are considered as a pair of disjoint sets. Each PT intends to be matched with a certain ST for the sake of achieving its target transmit rate, whilst simultaneously minimizing its transmit power. A ST, on the other hand, intends to be matched with an appropriate PT in order to win a transmission opportunity within the licensed band for its own traffic, whilst simultaneously minimizing its total transmit power. Hence, the spectrum sharing problem can be formulated as a matching game, which is capable of producing a stable matching between the PTs and the STs. Based on the scenario discussed in Section II, we design a DWWRS-MAS relying on a PT proposal rule for solving the matching game formulated.

B. THE PROPOSED DWWRS-MAS

Based on the proposed DWWRS-MAS, the PTs scale their transmit power into several levels, namely we have $P_{p_l} \in \{P_{p_1}, \ldots, P_{max}\}$. Each power level may be given by $P_{p_{l+1}} = P_{p_l} + \Delta$, where Δ denotes the PT's power control step size. In order to minimize the transmit power, PT_i first broadcasts its target receive Signal to Noise Ratio (SNR) $\gamma_{ps}[i, P_{PT}(i)]$, which has to be guaranteed by its cooperative partner, when PT_i consumes its lowest transmit power $P_{PT}(i) = P_{p_1}$ to convey its data and has a transmit rate requirement of $R^{req}_{PT_i} = \alpha C^{max}_{PT_i,PR_i}$ ($\alpha > 1$). The derivation of PT's proposal $\gamma_{ps}[i, P_{PT}(i)]$ will be discussed later. If no ST accepts the proposal of PT_i, PT_i has to increase its transmit power to the next level of $P_{PT}(i) = P_{p_{l+1}}$ and broadcast its reduced target-QoS $\gamma_{ps}[i, P_{PT}(i)]$ to all the STs, as shown in Table 1. When PT_i increases its transmit power, more STs may intend to be the cooperative partner of PT_i, because a lower total transmit power P_{ST} is required for satisfying the reduced target-QoS of PT_i. The PT_i repeats the above discovery procedure either until it finds an appropriate cooperative partner or until its transmit power achieves the maximum transmit power P_{max}. When the transmit power of PT_i is increased to the highest power level, namely $P_{PT}(i) = P_{max}$, PT_i has to directly transmit its data without cooperative transmission assistance, provided that PT_i still fails to select its cooperative partner with the maximum transmit power P_{max}, as seen in Table 1.

After receiving a proposal from PT_i, ST_m first calculates the total transmit power $P_{ST}(i, m)$ required for satisfying the transmit rate requirements of both PT_i and itself. If it is the case that the power $P_{ST}(i, m)$ does not exceed the maximum affordable transmit power P_{max}, namely we have $P_{ST}(i, m) \le P_{max}$, then ST_m accepts the proposal from PT_i, provided that ST_m has not been matched. If ST_m is already matched with any PT_j, ST_m may accept the proposal from PT_i for the sake of reducing its transmit power, provided that we have $P_{ST}(i, m) < P_{ST}(j, m)$. Based on our DWWRS-MAS, each ST only has a single cooperative partner. Hence, ST_m has to divorce its current cooperative pair $\mathcal{O}(PT_j, ST_m)$ and proceeds to form the new pair of $\mathcal{O}(PT_i, ST_m)$.

If the cooperative pair $\mathcal{O}(PT_j, ST_m)$ is divorced, PT_j will find another cooperative partner, which is capable of successfully satisfying the target-QoS $\gamma_{ps}[j, P_{PT}(j, m)]$ that was guaranteed by the previous cooperative partner of PT_j, namely by ST_m, for the sake of acquiring cooperative transmission assistance without increasing the transmit power of PT_j. If no STs intend to become the cooperative partner of PT_j for guaranteeing the target-QoS $\gamma_{ps}[j, P_{PT}(j, m)]$, PT_j increases its transmit power to the next higher power level according to $P_{PT}(i) = P_{p_{l+1}}$ and repeats the above procedures, as shown in Table 1.

TABLE 1. The proposed DWWRS-MAS.

```
Initialization:
    $PT_i$ sets its power as $P_{PT}(i) = P_{p_1} \forall i \in \mathcal{I}$
Repeat:
    for all $i \in \mathcal{I}$ $PT_i$ do
        if $PT_i$ is not matched
            if $P_{PT}(i) \le P_{max}$
                ▷ calculates its target-QoS $\gamma_{ps}[i, P_{PT}(i)]$
                  based on its power $P_{PT}(i)$.
                ▷ broadcasts its proposal $\gamma_{ps}[i, P_{PT}(i)]$ to all STs.
        else
                ▷ directly transmits its data to $PR_i$.
    for all $m \in \mathcal{M}$ $ST_m$ do
        if receives a proposal from $PT_i$
            calculates total power $P_{ST}(i, m)$.
            if $P_{ST}(i, m) \le P_{max}$
                if $ST_m$ is not matched
                    ▷ accepts the proposal of $PT_i$.
                    ▷ sends its power $P_{ST}(i, m)$ to $PT_i$.
                    ▷ waits for matching conformation from $PT_i$.
                if $ST_m$ is matched with $PT_{I^*(m)}$
                    if $P_{ST}(i, m) < P_{ST}(I^*(m), m)$
                        ▷ accepts the proposal of $PT_i$.
                        ▷ sends its power $P_{ST}(i, m)$ to $PT_i$.
                        ▷ waits for matching conformation
                          from $PT_i$.
    for all $i \in \mathcal{I}$ $PT_i$ do
        if its proposal is accepted by a single ST $ST_m$
            ▷ sends matching confirmation message to $ST_m$.
            ▷ sets $P^{current}_{PT}(i) = P_{p_l}$.
            ▷ $PT_i$ is matched with $ST_m$.
        if its proposal is accepted by more than one STs
            ▷ sends matching confirmation message to $ST_{\hat{m}}$
              which consumes the lowest power $P_{ST}(i, \hat{m})$ ¹.
            ▷ sets $P^{current}_{PT}(i) = P_{p_l}$.
            ▷ $PT_i$ is matched with $ST_{\hat{m}}$.
        if no ST accepts its proposal
            ▷ increases transmit power to next level
              which is given by: $P_{PT}(i) = P_{PT}(i) + \Delta$.
    for all $m \in \mathcal{M}$ $ST_m$ do
        if receives matching confirmation message from $PT_i$
            ▷ if is already matched with $PT_{I^*(m)}$
                ⋆ rejects $PT_{I^*(m)}$.
            ▷ sets current power as $P^{current}_{ST}(m) = P_{ST}(i, m)$.
            ▷ $ST_m$ is matched with $PT_i$.
    for all $i \in \mathcal{I}$ $PT_i$ do
        if is already matched with $ST_{M^*(i)}$
            if $ST_{M^*(i)}$ divorces matched pair $\mathcal{O}(PT_i, ST_{M^*(i)})$
                ▷ $PT_i$ sets its power as $P_{PT}(i) = P^{current}_{PT}$.
                ▷ $PT_i$ is not matched.
Until: no PT broadcasts its proposal.
```

[1] The lifetime of a secondary network may be reduced when a higher power is consumed by its constituent STs. A longer lifetime of the secondary network may provide a higher cooperative probability for the PTs. Hence, if more than one STs may fulfill the same power saving and rate requirement, the PT_i may be matched with one specific ST which consumes the lowest transmit power for a higher cooperative chance in the further.

According to the PT's transmit rate requirement of $\alpha C^{max}_{PT,PR}$ and to the current transmit power level $P_{PT}(i) = P_{p_l}$, PT_i calculates the target receive SNR of $\gamma_{ps}[i, P_{PT}(i)]$

as its proposal. More explicitly, PR_i in our system exploits the classic Chase combining scheme [21] for combining direct transmission with the duplicated data frame transmitted independently by the cooperative partner of PT_i in order to achieve rate improvements. Therefore, the PT's aggregated rate achieved by using frame combining is given by $\alpha C^{max}_{PT_i,PR_i} = \frac{T}{2}\log_2\{1 + \gamma^{(1)}_{PT_i,PR_i}[i, P_{PT}(i)] + \gamma_{ps}[i, P_{PT}(i)]\}$, $\alpha > 1$, where $\gamma^{(1)}_{PT_i,PR_i}[i, P_{PT}(i)]$ denotes the receive SNR at PR_i related to the direct transmission. Based on the scenario considered, PT_i calculates its proposal as $\gamma_{ps}[i, P_{PT}(i)] = 2^{\frac{2}{T}\alpha C^{max}_{PT_i,PR_i}} - \gamma^{(1)}_{PT_i,PR_i}[i, P_{PT}(i)] - 1$. It is worth noting that the target receive SNR of $\gamma_{ps}[i, P_{PT}(i)]$ is reduced, when PT_i increases its transmit power $P_{PT}(i)$. This implies that more STs may intend to become the cooperative partner of PT_i, when PT_i increases its transmit power, because a lower transmit power P_{ST} is required for satisfying the PT's reduced target-QoS $\gamma_{ps}[i, P_{p_{l+1}}]$.

IV. STABILITY ANALYSIS

Based on matching theory [22], the algorithmic stability of our DWWRS-MAS is discussed in Section IV-A. Furthermore, considering the bursty nature of the transmissions from the PTs and STs, Section IV-B analyses the queueing stability of the proposed DWWRS-MAS relying on queueing theory [23].

A. ALGORITHMIC STABILITY OF THE PROPOSED DWWRS-MAS

A common and realistic assumption in a cooperative cognitive network is that both the PT and the ST focus their efforts on optimizing their own OF when they contend with other PTs or STs. Hence, based on the matching theory [22], this section analyzes the algorithmic stability of the proposed DWWRS-MAS by considering the selfish behaviour of both the PTs and the STs. Before analyzing the algorithmic stability of our DWWRS-MAS, let us first introduce the definition of ‘stable matching’.

Based on the matching theory, we refer to (PT_i, ST_m) as a blocking pair, if both PT_i and ST_m intend to reduce their transmit power by divorcing their current cooperative pairs $\mathcal{O}(PT_i, ST_{M^*(i)})$ as well as $\mathcal{O}(PT_{I^*(m)}, ST_m)$, respectively, and by forming a new cooperative pair $\mathcal{O}(PT_i, ST_m)$, where we have $M^*(i) \neq m$ and $I^*(m) \neq i$. Furthermore, an individual PT or ST may be referred as a blocking individual, if it prefers not to be matched at all, rather than being matched with its current partner. The set of pairs, which are constructed according to the proposed DWWRS-MAS are linked together by the cooperative matching $X_{DWWRS-MAS}$. Hence, a cooperative matching $X_{DWWRS-MAS}$ is considered to be stable, when no blocking pair and/or no blocking individual exists. Therefore, we have the following proposition.

Proposition 1: The proposed DWWRS-MAS of Section III produces a stable cooperative matching. See Appendix A for the proof.

Proposition 1 illustrates that the specific PT and ST, which constitute a cooperative pair according to our DWWRS-MAS cannot simultaneously reduce their transmit power, if they select another ST or PT as their cooperative partner.

B. QUEUEING STABILITY OF DWWRS-MAS

1) QUEUEING MODEL

Based on our DWWRS-MAS, we consider a cooperative queueing system, where each PT has a single queue for storing its data, while each ST is equipped with two queues, namely one for storing the data from its cooperative partner and one for its own data, as shown in Fig 2. In order to simplify our system stability analysis, we consider a simple CSLS having two PTPs and multiple STPs. All the nodes are assumed to have infinite-capacity buffers for storing their incoming packets. We assume that each PT's data packet is transmitted within a specific time-slot (TS). Each PT transmits one data frame in each TS, which is assumed to be long enough for implementing the proposed DWWRS-MAS and for transmitting the data. Furthermore, we assume a network-wide synchronisation. The packet arrival processes at each node are assumed to be independent and stationary with a mean of λ_{PT_i} packets per slot for PT_i and λ_{ST_m} packets per slot for ST_m.

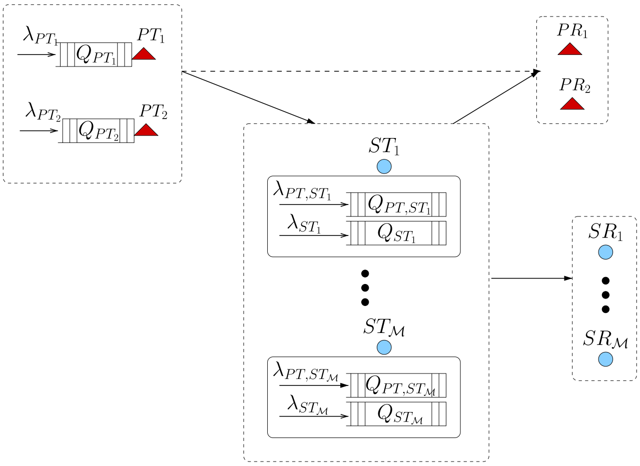


FIGURE 2. The queueing model of a cooperative spectrum leasing system, which supports two PTPs and multiple STPs as well as relies on the proposed DWWRS-MAS.

For source nodes generating bursty tele-traffic, the stability of a communication network is one of its fundamental performance measures. A network may be considered to be stable for a certain arrival rate vector, provided that all of its queues are stable, which implies that the length of all the queues remains finite [24]. According to Loynes' theorem [25], if the arrival and departure processes of a queueing system are stationary, the i_{th} queue is stable, when the average arrival rate λ_i is lower than the average departure rate μ_i $(\lambda_i < \mu_i)$. Based on our assumptions, the stability of the queues may be verified with the aid of Loynes' theorem [25].

2) STABILITY OF THE PRIMARY TRANSMITTER'S QUEUE

Based on the proposed DWWRS-MAS, the PT's data may be successfully delivered to the destination with the aid of cooperative transmission from its cooperative partner or may be directly transmitted from the PT to the destination, as seen in Table 1. Hence, the maximum departure rate at the PT PT_i is formulated as:

$$\mu_{PT_i}^{max} = \mu_{PT_i}^{coop} + \mu_{PT_i}^{noncoop}. \tag{14}$$

Let us now consider each term in detail.

a: DEPARTURE RATE OF $\mu_{PT_i}^{coop}$

According to the proposed DWWRS-MAS, PT_i may successfully select ST_m as its cooperative partner in one of the following three scenarios: (1) In scenario 1, we assume that only PT_i has data to send in the current time slot and its candidate cooperative partner set is not empty, i.e. we have $\mathcal{C}_{PT}(i) \nsubseteq \emptyset$. Then PT_i is capable of acquiring cooperative transmission assistance according to the proposed DWWRS-MAS; (2) In scenario 2, we consider a network, where *multiple* STs contend for the transmission opportunity granted by PT_i and the other PT also has data to send in the current time slot. Then at least one ST, say ST_m is capable of forming a cooperative pair of $\mathcal{O}(PT_i, ST_m)$ with PT_i, regardless whether both PT_i and the other PT contends for the same candidate cooperative partners or not, based on the proposed DWWRS-MAS; (3) In scenario 3, we assume that ST_m is the *only* candidate cooperative partner of PT_i and that another PT say PT_j also has data to send in the current time slot. Then, ST_m may agree to become the cooperative partner of PT_i, if either no PT contends with PT_i for acquiring cooperative transmission assistance from ST_m or PT_i is the winner of the PTs' competition. Based on the above discussions, the average cooperative departure rate at PT_i may be written as:

$$\begin{aligned}
\mu_{PT_i}^{coop} = {} & \underbrace{\mathbb{P}\{Q_{PT_j} = 0|_{i\neq j}\}}_{Q_{PT_j}\text{ is empty}} \cdot \underbrace{\mathbb{E}\Big\{\mathbb{P}\{\widetilde{M}(i) > 0\}\Big\}}_{\mathcal{C}_{PT}(i) \neq \emptyset} \\
& + \underbrace{\mathbb{P}\{Q_{PT_j} \neq 0|_{i\neq j}\}}_{PT_j\text{ has data to send}} \\
& \cdot \underbrace{\mathbb{E}\Big\{\mathbb{P}\{T_{PT_i}^{coop}|\widetilde{M}(i) > 1\} + \mathbb{P}\{T_{PT_i}^{coop}|\widetilde{M}(i) = 1\}\Big\}}_{PT_i\text{ has cooperative partner when }PT_j\text{ is also active}},
\end{aligned} \tag{15}$$

where $\widetilde{M}(i)$ denotes the size of the candidate cooperative partner set $\mathcal{C}_{PT}(i)$ of PT_i, while $\mathbb{P}\{Q_{PT_j} \neq 0\}$ indicates that PT_j has data to send at the beginning of the current time slot. According to Little's theorem the probability that the SN's queue is not empty is given by $\mathbb{P}\{Q_{PT_j} \neq 0\} = \lambda_{PT_j}/\mu_{PT_j}^{max}$. Furthermore, $\mathbb{P}\{T_{PT_i}^{coop}|\widetilde{M}(i) > 1\}$ denotes the probability that PT_i is capable of acquiring cooperative transmission assistance in Scenario 2, where it has *multiple* candidate cooperative partners. The expression $\mathbb{P}\{T_{PT_i}^{coop}|\widetilde{M}(i) = 1\}$ denotes the probability of the event that the data of PT_i is delivered with the aid of cooperative transmission in Scenario 3, where PT_i has *only one* candidate cooperative partner, which may be formulated by Eq (17), as shown at the bottom of this page.

b: DEPARTURE RATE OF $\mu_{PT_i}^{noncoop}$

According to the proposed DWWRS-MAS in Section III, PT_i may not be capable of acquiring cooperative transmission assistance in one of the following two scenarios: (1) When *no* ST is capable of satisfying the transmit rate requirements of both PT_i and itself even at the highest power level of PT_i, namely when we have $P_{PT}(i) = P_{max}$, then PT_i has to directly transmit its data to the destination without cooperative transmission, as seen in Table 1; (2) When both PT_i and PT_j have data to send at the beginning of current time slot and PT_i has *only a single* candidate cooperative partner, PT_i may not be capable of acquiring cooperative transmission assistance if PT_i fails to win the PTs' competition. Based on the above discussions, the average non-cooperative departure rate at PT_i may be written as:

$$\begin{aligned}
\mu_{PT_i}^{noncoop} = {} & \underbrace{\mathbb{P}\{\widetilde{M}(i) = 0\}}_{\text{no ST can satisfy the transmit rate requirement of }PT_i} \\
& + \underbrace{\mathbb{P}\{Q_{PT_j} \neq 0|_{i\neq j}\} \cdot \mathbb{P}\{T_{PT_i}^{noncoop}|\widetilde{M}(i) = 1\}}_{PT_i\text{ fails to win the PTs' contention}}.
\end{aligned} \tag{17}$$

According to the behaviour of PT_i shown in Table 1, when it has only one candidate cooperative partner, namely ST_m, the probability of $\mathbb{P}\{T_{PT_i}^{noncoop}|\widetilde{M}(i) = 1\}$ in Eq (17) may be characterized by Eq (18), as shown at the bottom of this page.

$$\begin{aligned}
\mathbb{P}\{T_{PT_i}^{coop}|\widetilde{M}(i) = 1\} = {} & \underbrace{\mathbb{P}\{I^*(\widehat{M}(i)) = i|\widetilde{M}(i) = 1, \widetilde{M}(j) = 0\}}_{\text{Scenario 3.1: only }PT_i\text{ has candidate cooperative partner}} + \underbrace{\mathbb{P}\{I^*(\widehat{M}(i)) = i|\widetilde{M}(i) = 1, \widetilde{M}(j) > 0, \widehat{M}(i) \neq \widehat{M}(j), i \neq j\}}_{\text{Scenario 3.2: }PT_i\text{ and }PT_j\text{ have different the winner of STs' competition}} \\
& + \underbrace{\mathbb{P}\{I^*(\widehat{M}(i)) = i|\widetilde{M}(i) = 1, \widetilde{M}(j) > 0, \widehat{M}(i) = \widehat{M}(j), i \neq j\}}_{\text{Scenario 3.3: }PT_i\text{ wins the PTs' competition}}
\end{aligned} \tag{16}$$

$$\begin{aligned}
\mathbb{P}\{T_{PT_i}^{noncoop}|\widetilde{M}(i) = 1\} = {} & \underbrace{\mathbb{P}\{I^*(\widehat{M}(i)) = j|\widetilde{M}(i) = 1, \widetilde{M}(j) = 1, \widehat{M}(i) = \widehat{M}(j), i \neq j\}}_{\mathcal{C}_{PT}(i) = \{ST_m\},\ \widetilde{M}(j) = 1,\text{ but }ST_m\text{ selects }PT_j} \\
& + \underbrace{\mathbb{P}\{I^*(\widehat{M}(i)) = j|\widetilde{M}(i) = 1, \widetilde{M}(j) > 1, \widehat{M}(i) = \widehat{M}(j), i \neq j\}}_{\mathcal{C}_{PT}(i) = \{ST_m\},\ \widetilde{M}(j) > 1,\text{ but }ST_m\text{ selects }PT_j}.
\end{aligned} \tag{18}$$

According to Eq (14), the total departure rate at PT_i in our system is characterized by the sum of the cooperative departure rate of Eq (15) and that of its non-cooperative counterpart in Eq (17). Hence, the queue of PT_i is stable, as long as we satisfy $\lambda_{PT_i} < \mu_{PT_i}^{max}$.

3) STABILITY OF THE SECONDARY SOURCE NODE'S QUEUE

a: STABILITY OF Q_{PT,ST_m}

In order to support cooperative transmissions, the ST ST_m is assumed to rely on the pair of queues Q_{ST_m} and Q_{PT,ST_m} for buffering both its own data and the PT's data, respectively, as shown in Fig 2. Based on our DWWRS-MAS, ST_m stores the PTs' data in Q_{PT,ST_m}, if the following two conditions are satisfied: (1) at least one PT has data to send at the beginning of the current time slot; (2) ST_m has a cooperative partner, namely we have $I^*(m) \neq 0$. Hence, the arrival rate of the PT's data at ST_m achieved in the scenario of having two PTPs as shown in Fig 2 may be written as:

$$\begin{aligned}&\lambda_{PT,ST_m}\\&\quad = \underbrace{\sum_{i=1}^{2}\Big(\mathbb{P}\{Q_{PT_i} \neq 0\}\cdot\mathbb{P}\{Q_{PT_j} = 0|_{i\neq j}\}\cdot\mathbb{P}\{T_{ST_m}^{(1)}(i)\}\Big),}_{\text{only one PT has data to send}}\\&\qquad + \underbrace{\prod_{i=1}^{2}\mathbb{P}\{Q_{PT_i} \neq 0\}\cdot\mathbb{P}\{T_{ST_m}^{(2)}\}}_{\text{both PTs have data to send}} \qquad (19)\end{aligned}$$

where $\mathbb{P}\{T_{ST_m}^{(1)}(i)\}$ represents the probability that ST_m and PT_i form a cooperative partner, when only PT_i has data to send at the beginning of the current time slot, which may be formulated as $\mathbb{P}\{T_{ST_m}^{(1)}(i)\} = \mathbb{P}\{M^*(i) = m|\widetilde{M}(i) = 1\} + \mathbb{P}\{M^*(i) = m|\widetilde{M}(i) > 1\}$, where $\mathbb{P}\{M^*(i) = m|\widetilde{M}(i) = 1\}$ denotes the probability that ST_m and PT_i constitute a cooperative pair when we have $\mathcal{C}_{PT}(i) = \{ST_m\}$ and only PT_i has data to send. Furthermore, the expression of $\mathbb{P}\{M^*(i)=m|\widetilde{M}(i) > 1\}$ represents the probability that PT_i forms a cooperative pair with ST_m, which is the winner of the STs' competition, when only PT_i has data to send and multiple STs become the candidate cooperative partners of PT_i, namely when we have $\widetilde{M}(i) > 1$.

Let us now introduce the notation $\mathbb{P}\{T_{ST_m}^{(2)}\}$, which denotes the probability that ST_m is capable of acquiring a cooperative transmission opportunity leased by its cooperative partner, when both PT_1 and PT_2 have data to send at the beginning of the current time slot. Hence, the probability of $\mathbb{P}\{T_{ST_m}^{(2)}\}$ may be formulated as $\mathbb{P}\{T_{ST_m}^{(2)}\} = \mathbb{P}\{T_{ST_m}|M_1^* = m\} + \mathbb{P}\{T_{ST_m}|M_2^* = m\}$, where $\mathbb{P}\{T_{ST_m}|M_1^* = m\}$ denotes the probability of the event that ST_m wins over a cooperative partner. Furthermore, $\mathbb{P}\{T_{ST_m}|M_2^* = m\}$ denotes the probability of the specific event that ST_m is selected by its cooperative partner $PT_{I^*(m)}$, when $PT_{I^*(m)}$ fails to win the PTs' competition for acquiring a cooperative transmission assistance from the winner of the STs' competition, say from ST_n.

When ST_m and PT_i constitute a cooperative pair, ST_m provides a data output for both the relaying queue Q_{PT,ST_m} and for the data queue Q_{ST_m} by exploiting superposition coding. In order to decouple the interaction between these two queues, we assume that if the ST's data queue Q_{ST_m} is empty, but Q_{PT,ST_m} has packets in its buffer, then the ST ST_m will superimpose the PT's data on a "dummy" packet. According to the proposed DWWRS-MAS, ST_m may be granted a transmission opportunity for conveying data in the queue Q_{PT,ST_m} and Q_{ST_m}, provided that both of the following two conditions are satisfied: (1) At least one PT has data to send at the beginning of the current time slot; (2) The ST ST_m becomes the cooperative partner of an active PT.

Therefore, the departure rate of the relaying queue Q_{PT,ST_m} may be expressed as:

$$\begin{aligned}\mu_{PT,ST_m} &= \sum_{i=1}^{2}\Big(\mathbb{P}\{Q_{PT_i} \neq 0\}\cdot\mathbb{P}\{Q_{PT_j} = 0|_{i\neq j}\}\\&\quad\cdot\mathbb{P}\{T_{ST_m}^{(1)}(i)\}\Big) + \prod_{i=1}^{2}\mathbb{P}\{Q_{PT_i} \neq 0\}\cdot\mathbb{P}\{T_{ST_m}^{(2)}\}.\end{aligned} \qquad (20)$$

By composing the arrival rate of the PT's data at ST_m, according to Eq (19) and the departure rate of the relaying queue Q_{PT,ST_m} in Eq (20), we have:

$$\lambda_{PT,ST_m} = \mu_{PT,ST_m}. \qquad (21)$$

The fundamental goal of the proposed DWWRS-MAS also transpires from Eq (21), namely that each arriving data transmission request will always be satisfied immediately in the relaying queue Q_{PT,ST_m}. Hence, the relaying queue Q_{PT,ST_m} always remains empty.

b: STABILITY OF Q_{ST_m}

Based on the proposed DWWRS-MAS, the ST ST_m jointly encodes a packet of its own data in the data queue Q_{ST_m} and a packet of the PT's data in the relaying queue Q_{PT,ST_m} by superposition coding, provided that ST_m constitutes a cooperative pair with one of the PTs. Hence, the queues Q_{PT,ST_m} and Q_{ST_m} have the same average departure rate, namely we have $\mu_{ST_m} = \mu_{PT,ST_m}$. Based on the above analysis, the stability of the relay's data queue requires $\lambda_{ST_m} < \mu_{ST_m}$.

V. SIMULATION RESULTS

A. SIMULATION CONFIGURATION

In order to evaluate the achievable performance of the proposed scheme, we consider a specific scenario where both the primary transmitters and primary receivers are randomly located on the opposite sides of the entire network area. Each of the secondary transmission pairs (ST, SR) are randomly distributed in this scenario across the entire network's area. The primary network has two PTPs, while the number of secondary transmission pairs ranges from $\mathcal{M} = 5$ to $\mathcal{M} = 11$

nodes for the sake of evaluating the influence of the network's size on the system's performance. The transmit rate requirements of the PT and ST are equal to $\alpha C_{PT,PR}^{max}$ and $\beta C_{ST,SR}^{max}$ respectively, where α is the PT's factor of greediness while β is the ST's factor of greediness. In order to investigate the performance of the scenario having more PTPs, the number of PTPs will be increased to $\mathcal{I} = 5$ and $\mathcal{I} = 8$ in Section V-E. Furthermore, aiming for evaluating the system's queueing stability, we considered a symmetric scenario having two PTs and two STs as well as a common destination D, where all the nodes have fixed positions. More explicitly, the distance from each PT to the destination is the same, while ST_1 is allocated in the middle of the link between PT_1 and D. Another ST ST_2 is in the middle of the link between PT_2 and D.

We consider a centralized cooperative system (CCS-1) as the cooperative benchmarker of our scheme. The centralized controller in CCS-1 relies on an optimal algorithm for minimizing the total transmit power of all the PTs and STs, whilst exploiting the Channel State Information (CSI) knowledge of all the links. Additionally, we also introduce a random cooperative spectrum leasing system (R-CSLS), where a PT randomly selects a ST as its cooperative partner, if both the PT's and ST's transmit rate requirement can be satisfied by forming this cooperative pair. In order to evaluate the benefits of our scheme, two non-cooperative systems (NCS) are introduced as the benchmarkers for our comparisons. We compare the system's achievable total transmit rate (TTR) constituted by the sum of all the PTs' and STs' transmit rate to that of the first non-cooperative system (nCS-1), which dissipates the same total transmission power as our CSLS. Additionally, we compare the total transmission power to that of the second non-cooperative system (nCS-2), which is capable of achieving the same TTR as our CSLS. All the assumptions mentioned in Section II are exploited by the benchmarkers of our scheme.

B. COOPERATION PROBABILITY

Fig 3 compares the successful cooperation probability of the PTs achieved by our DWWRS-MAS, and by the R-CSLS as well as by the CCS-1 versus different-size secondary networks for $\mathcal{I} = 2$, $\alpha = 2.0$ and $\beta = 0.5$. Given the size of the secondary network, our DWWRS-MAS is capable of providing a higher cooperation probability for the PTs and more transmission opportunities for the secondary transmission pairs than the R-CSLS, which again relies on a random relay selection scheme, as seen in Fig 3. By contrast, the cooperation probability achieved by our DWWRS-MAS is lower than that achieved by the centralized systems CCS-1, as seen in Fig 3. Based on the global CSI knowledge, the centralized controller of CCS-1 is capable of finding the optimal cooperative pairs for the sake of optimizing the corresponding OFs, albeit this is achieved at the cost of a considerable computational complexity. Observe in Fig 3 that the cooperation probability achieved in all the cooperative systems considered in this section is increased, when more STPs intends to access the licensed spectrum, because the probability of the event that the STs are capable of successfully forwarding the superposition-coded data is increased, as the secondary network becomes larger. As seen in Fig 3, the cooperation probability curve of our DWWRS-MAS gradually approaches that of the centralized system CCS-1, when network has more STPs. When the secondary network size is increased, both the PTs and STs may have more candidate cooperative partners. Hence, the probability that multiple PTs contend for a single ST may be reduced and the loser of the contention has a higher probability of forming a cooperative pair with other STs in the larger network. This phenomenon reduces the gap between the cooperation probability achieved by the proposed DWWRS-MAS and those achieved by CCS-1. Compared to the cooperation probability achieved by R-CSLS, the advantage of the proposed DWWRS-MAS becomes more evident, as the number of STPs is increased due to the increased number of candidate cooperative partners of both the PTs and STs, as seen in Fig 3.

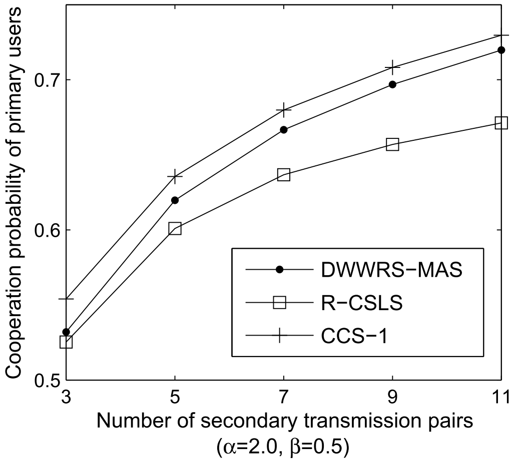


FIGURE 3. Cooperation probability of the PTs versus the number of secondary users for $\mathcal{I} = 2$, $\alpha = 2.0$ and $\beta = 0.5$.

C. TRANSMIT POWER CONSUMPTION

Let us commence by first evaluating the system's total transmit power (STTP) for the cooperative systems considered in this section, namely that of the proposed DWWRS-MAS, CCS-1 as well as R-CSLS for $\mathcal{I} = 2$, $\alpha = 2.0$ and $\beta = 0.5$. The STTP is given by the sum of the transmit power of all the PTs and STs, which were granted transmission opportunities. This is formulated as $\frac{1}{N_{all}} \cdot \sum_{x=1}^{N_{all}} \left[\sum_{i=1}^{\mathcal{I}} P_{PT}^{x}(i) \right] + \frac{1}{N_{all}} \cdot \sum_{x=1}^{N_{all}} \left[\sum_{m=1}^{\mathcal{M}} P_{ST}^{x}(m) \right]$, where N_{all} denotes the total number of instances of our DWWRS-MAS in the Monte Carlo simulation. Moreover, $P_{PT}^{x}(i)$ represents the transmit power consumed by PT_i, whilst relying on either the cooperative transmission or the direct transmission of its data to PR_i during the x-th instance of the Monte Carlo simulation. Furthermore, $P_{ST}^{x}(m)$ denotes the transmit power dissipated

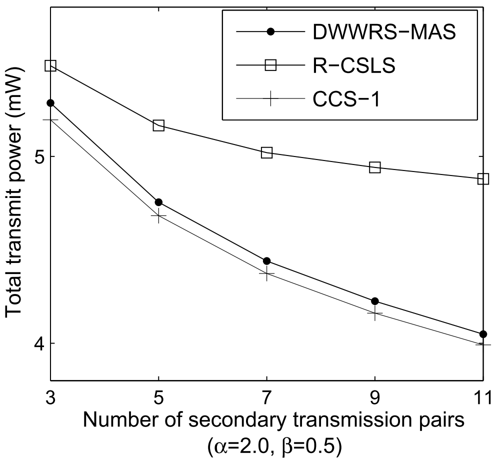


FIGURE 4. **The system's total transmit power versus the number of secondary users for $\mathcal{I} = 2$, $\alpha = 2.0$ and $\beta = 0.5$.**

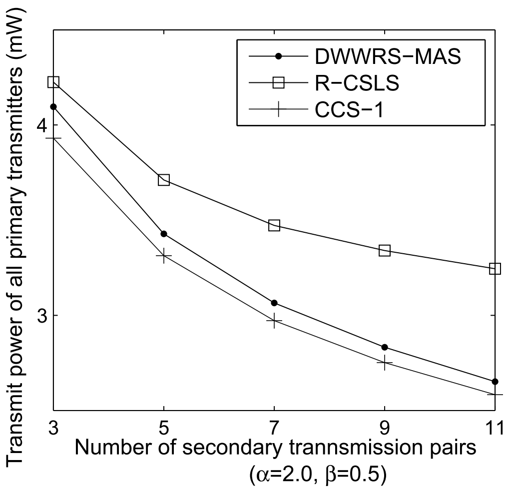


FIGURE 5. **The transmit power of all PTs versus the number of secondary users for $\mathcal{I} = 2$, $\alpha = 2.0$ and $\beta = 0.5$.**

by ST_m, when successfully conveying the superposition-coded data during the x-th instance of the Monte Carlo simulation. If ST_m fails to win a transmission opportunity during the x-th instance of the Monte Carlo simulation, the $P_{ST}^x(m)$ is equal to zero. Hence, the term in the first part formulates the average total transmit power of all the PTs dissipated, when transmitting their data with or without the aid of cooperative transmission. Furthermore, the term in the second part formulates the average total transmit power of all the STs dissipated, while conveying the superposition-coded data.

Observe in Fig 4 that our DWWRS-MAS is capable of saving considerably more STTP than R-CSLS. This is not unexpected, because the proposed DWWRS-MAS was designed for the sake of minimizing the transmit power of both PTs and STs. Based on the global CSI information knowledge, the centralized controller selects the optimal cooperative pairs for the sake of minimizing the system's total transmit power in CCS-1. Hence, the users of CCS-1 consume the lowest transmit power, as seen in Fig 4. It is worth noting that the STTP curve of our DWWRS-MAS which selects the cooperative pairs in a *distributed* fashion, i.e. without a central controller, approaches that of the *centralized* system considered in this section, as shown in Fig 4. When the network has a high number of secondary transmission pairs, the probability of beneficial cooperative pairs, which are capable of approaching the global optimum of the system's OFs is increased. Furthermore, based on the above discussions, it becomes plausible that the cooperation probability of the PTs is also increased as the secondary network becomes larger, as seen in Fig 3. Hence, the STTP consumed both by our DWWRS-MAS and by the benchmark systems is reduced, when more STs intend to access the primary network.

Fig 5 shows our comparison between the total transmit power of all PTs (TPP) consumed in the proposed DWWRS-MAS versus that dissipated by the benchmark systems namely CCS-1 and R-CSLS for $\mathcal{I} = 2$, $\alpha = 2.0$ and $\beta = 0.5$. In this context the TPP is formulated as: $\frac{1}{N_{all}} \cdot \sum_{x=1}^{N_{all}} \left[\sum_{i=1}^{\mathcal{I}} P_{PT}^x(i) \right]$, where N_{all} denotes the total number of instances of our DWWRS-MAS in the Monte Carlo simulation. Furthermore, $P_{PT}^x(i)$ represents the transmit power consumed by PT_i, whilst relying on either the cooperative transmission or on the direct transmission of its data to PR_i during the x-th instance of the Monte Carlo simulation. The highest TPP is consumed in R-CSLS, where the cooperative pairs are randomly formed, as seen in Fig 5. Compared to the TPP of R-CSLS, our DWWRS-MAS is capable of saving valuable TPP, which may become as high as 90% of that saved in CCS-1 for $\mathcal{M} = 11$, as seen in Fig 5. Based on the above discussions, it becomes plausible that the lack of global information reduces the cooperation probability, whilst increasing the TPP of the proposed DWWRS-MAS, as shown in Fig 3 and Fig 5, respectively. When the secondary network becomes larger, the increased probability of meritorious cooperation pairs combined with a higher cooperation probability reduces the TPP in all the cooperative systems considered in this section, namely in the proposed DWWRS-MAS as well as in the CCS-1 and R-CSLS, as seen in Fig 5. This phenomenon widens the gap between the curves of our DWWRS-MAS as well as the R-CSLS, whilst reducing the discrepancy between our DWWRS-MAS and CCS-1, as seen in Fig 5.

D. COMPARISON WITH NON-COOPERATIVE SYSTEM

In this section, we introduce two non-cooperative systems, namely nCS-1 and nCS-2 as the benchmark systems for characterizing both the transmit power and transmit rate of our DWWRS-MAS. As described in Section V-A, nCS-1 consumes the same STTP as our DWWRS-MAS, while nCS-2 is capable of achieving the same TTR as the proposed DWWRS-MAS. Table 2 lists the system's transmit rate

TABLE 2. Performance comparison between our cooperative system and the non-cooperative systems nCS-1 and nCS-2. STRaR: system's transmit rate ratio; STPowR: system's transmit power ratio.

Number of STs	STRaR $\frac{\mathbb{E}\{R_{nCS-1}\}}{\mathbb{E}\{R_{DWWRS-MAS}\}}$	STPowR $\frac{\mathbb{E}\{P_{nCS-2}\}}{\mathbb{E}\{P_{DWWRS-MAS}\}}$
3	0.6084	1.7831
5	0.5459	2.3310
7	0.5070	2.9103
9	0.4730	3.6655
11	0.4504	4.4024

ratio (STRaR) and system's transmit power ratio (STPowR) for $\mathcal{I} = 2$, $\alpha = 2.0$ and $\beta = 0.5$, where STRaR is formulated as $\mathbb{E}\{R_{nCS-1}\}/\mathbb{E}\{R_{DWWRS-MAS})\}$, with R_{nCS-1} and $R_{DWWRS-MAS}$ denoting the achievable total transmit rate (TTR) of nCS-1 and of our DWWRS-MAS, respectively. Furthermore STPowR is given by $(\mathbb{E}\{P_{nCS-2}\}/\mathbb{E}\{P_{DWWRS-MAS})\}$, where P_{nCS-2} denotes the STTP dissipated by nCS-2 and $P_{DWWR-SMAS}$ is the STTP consumed in the proposed DWWRS-MAS. Observe in Table 2 that nCS-1 is capable of achieving 60% of the TTR achieved by our DWWRS-MAS in the scenario of supporting $\mathcal{M} = 3$ STPs, where our DWWRS-MAS consumes the most STTP. Based on the same STTP, we observe in Table 2 that the TTR achieved by nCS-1 is less than half of that achieved by our DWWRS-MAS, when the number of STPs is more than $\mathcal{M} = 7$. When aiming for achieving the same TTR, nCS-2 has to dissipate more than twice the STTP of our DWWRS-MAS, when the secondary network has more than $\mathcal{M} = 3$ STPs. Based on the above discussions, our DWWRS-MAS is capable of considerably saving STTP and simultaneously significantly improving the TTR, compared to the non-cooperative systems.

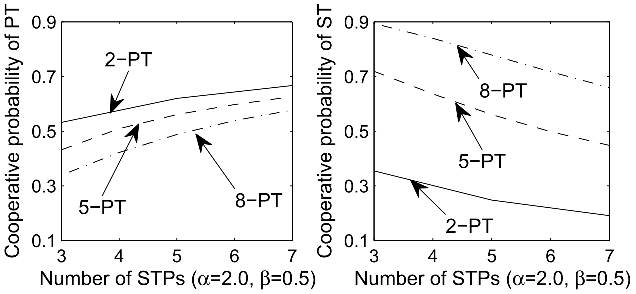


FIGURE 6. Average cooperation probability of each PT and of each ST versus the number of secondary users for $\alpha = 2.0$ and $\beta = 0.5$ versus the number of PTs relying on the proposed DWWRS-MAS.

E. EFFECT OF NUMBER OF PTPs

Fig 6 shows the comparison of the average cooperation probability of each PT and of each ST, when the primary network has $\mathcal{I} = 2$ PTPs, $\mathcal{I} = 5$ PTPs and $\mathcal{I} = 8$ PTPs. Given the size of the secondary network, observe in Fig 6 that more PTs might fail to find a cooperative partner as the number of PTPs is increased, because the contention between the PTs becomes more intense. By contrast, the cooperation probability of the STs is increased, when the primary network becomes larger as shown in Fig 6, because the STs benefit from more opportunities of accessing the licensed spectrum, as the primary network has more PTPs. When the secondary network becomes larger, the cooperation probability of the PTs is increased, since they benefit from having an increased probability of finding meritorious STs, as seen in Fig 6. By contrast, the cooperation probability of the STs is reduced, as the number of STPs is increased due to the more intense competition between the STs and owing to the increased probability of having deficient STs which cannot become the cooperative partner of the PT or cannot even become a candidate cooperative partner.

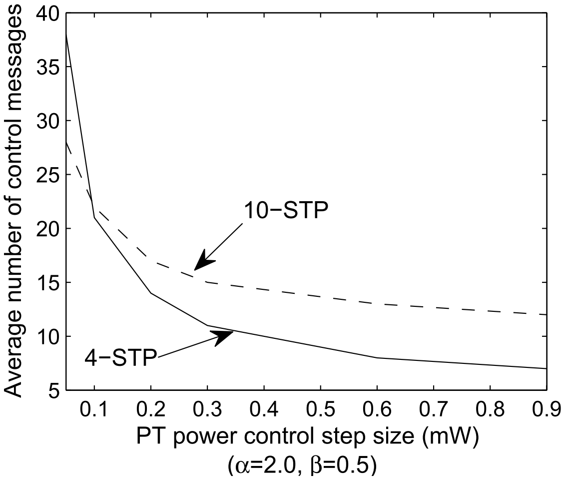


FIGURE 7. Number of control messages exchanged during the selection of the cooperative pairs in the network relying on the proposed DWWRS-MAS versus the PTs' transmit power control step size Δ for $\alpha = 2.0$ and $\beta = 0.5$.

F. EFFECT OF THE PT POWER CONTROL STEP SIZE

Based on the network having two PTPs, in this section we evaluate the effect of different transmit power control steps size Δ of the PTs on the performance of our DWWRS-MAS for $\alpha = 2.0$ and $\beta = 0.5$. To this effect, Fig 7 portrays the number of control messages required between the PTs and STs for selecting their cooperative partners in our DWWRS-MAS as a function of the PT transmit power control step size Δ. Observe in Fig 7 that the number of control messages is significantly reduced, as the step size Δ of the PTs' transmit power is increased in the range of $\Delta < 0.2$. For $\Delta > 0.2$, the number of control messages is slightly reduced, as Δ is increased, as seen in Fig 7. According to the proposed DWWRS-MAS, the PT increases its transmit power step by step, when it cannot find a cooperative partner at the current power level as seen in Table 1. Hence, the PTs have more legitimate transmit power levels for a smaller Δ. However, observe in Fig 7 that having a reduced step size Δ significantly increased the number of control messages exchanged before the PTs succeed in selecting an appropriate cooperative partner. By contrast, the PTs have less legitimate transmit power levels for a larger Δ. Hence, observe in Fig 7 that the average number of control messages exchanged between the PTs and STs is reduced from $\mathcal{N}_{control} = 11$ to $\mathcal{N}_{control} = 7$ for $\mathcal{M} = 4$ and from $\mathcal{N}_{control} = 15$ to $\mathcal{N}_{control} = 13$ for $\mathcal{M} = 10$, when Δ is increased from $\Delta = 0.3$ to $\Delta = 0.9$. When the secondary network becomes larger, the PTs benefit from having more candidate cooperative partners due to the increased probability of finding meritorious STs. Hence, more control messages are exchanged between the PTs and STs in the network having more STPs, as shown in Fig 7. As discussed above, the probability that the PTs find their cooperative partners, when they have a high transmit power level is increased upon increasing the PTs' transmit power control step size Δ. Hence, a higher STTP is dissipated for a larger Δ, as seen in Fig 8.

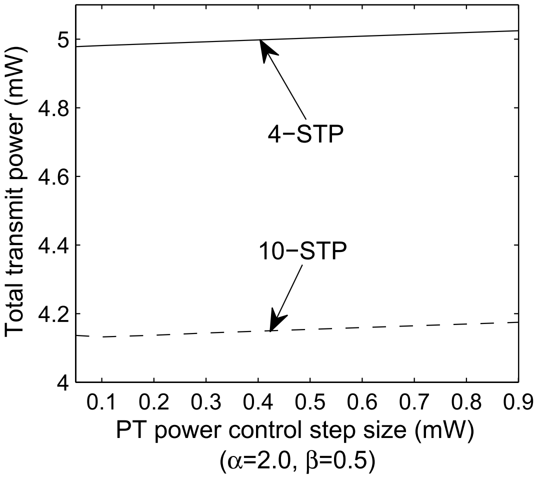


FIGURE 8. The system's total transmit power relying on the proposed DWWRS-MAS versus the PTs' transmit power control step size Δ for $\alpha = 2.0$ and $\beta = 0.5$.

G. STABLE THROUGHPUT

According to the proposed DWWRS-MAS the PTs' data may be delivered with the aid of cooperative transmission assistance from the STs, when the PTs and STs form cooperative pairs. If no ST can be the cooperative partner of a PT, this PT directly transmits its data to D. Hence, the maximum stable throughput of PT_1 formulated by Eq (14) is one packet per slot as shown in Fig 9. However, an increased transmit rate is achieved by the PTs with the aid of cooperative transmission assistance. Hence, the stable throughput of PT_1 achieved by the cooperative transmission $\mu_{PT_1}^{coop}$ is also shown in Fig 9. When the average arrival rate λ_{PT_2} is increased, the competition between PT_1 and PT_2 becomes more intense. Hence, $\mu_{PT_1}^{coop}$ is reduced, when PT_2 has more data to send, as seen in Fig 9.

Fig 10 shows the stable throughput of ST_1 and ST_2 in packets/slot achieved in three different scenarios for

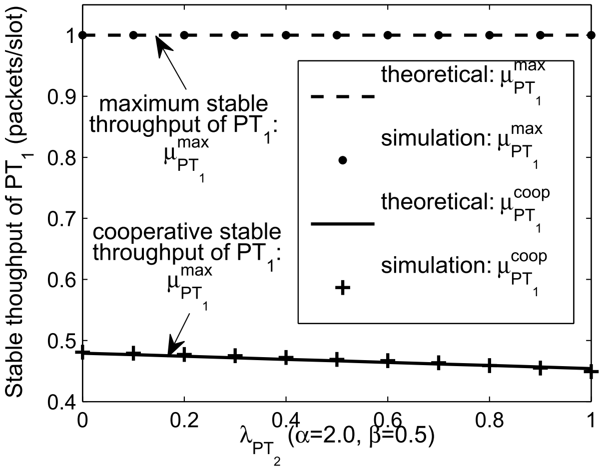


FIGURE 9. The stable throughput of PT_1 formulated by Eq (14) versus the arrival rate of λ_{PT_2} for $\alpha = 2.0$ and $\beta = 0.5$ for the network relying on the proposed DWWRS-MAS.

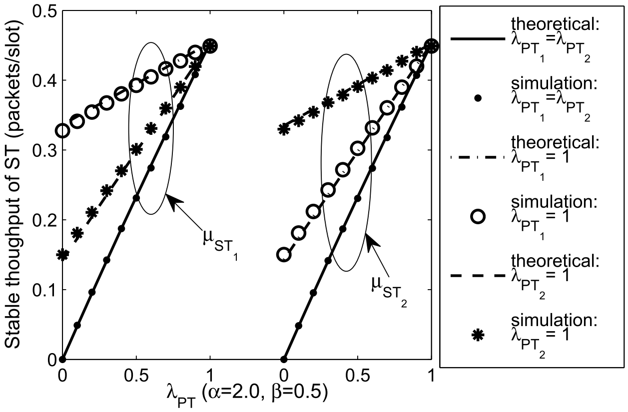


FIGURE 10. The stable throughput of the ST versus the arrival rate of λ_{PT_2} and λ_{PT_2} for $\alpha = 2.0$ and $\beta = 0.5$ for the network relying on the proposed DWWRS-MAS.

$\alpha = 2.0$ and $\beta = 0.5$, where PT_1 and PT_2 have the same average arrival rate, namely $\lambda_{PT_1} = \lambda_{PT_2}$ in Scenario 1. In Scenario 2, PT_1 always has data to send, namely we have $\lambda_{PT_1} = 1$, while λ_{PT_2} is increased from 0 to 1. By contrast, PT_2 always has data to send, while λ_{PT_1} varies from 0 to 1. Observe in Fig 10 that the stable throughput of both ST_1 and ST_2 is increased, as the arrival rate of the PTs becomes higher. As a benefit of our cooperative spectrum leasing system, the STs may be granted a transmission opportunity only when at least one PT has data to send, as mentioned in Section IV-B3. This phenomenon implies that the STs may be granted more frequent transmission opportunities, when the PTs have more packets to send. Hence, the STs' stable throughput are increased, as either λ_{PT_1} or λ_{PT_2} is increased. Observe in both Fig 9 and Fig 10 that the theoretical curve and the practical results almost overlap each other. Hence, our stability analysis of Section IV-B may be deemed accurate.

VI. CONCLUSIONS

In this paper, we developed a DWWRS-MAS for a CSLS hosting multiple PTPs and multiple STPs for the sake of minimizing the transmit power dissipated by the cooperative pair and for improving the transmit rate of the PTs as well as for granting transmission opportunities for the unlicensed STs. Based on our DWWRS-MAS, the best cooperative pairs were distributively selected. Furthermore, both the algorithmic stability and the queueing stability of the proposed DWWRS-MAS was analysed with the aid of the matching theory and the queueing theory. According to the definition of stable match, the proposed DWWRS-MAS is capable of producing stable cooperative pairs. Moreover, the performance of the proposed DWWRS-MAS is comparable to that achieved by the optimal centralized cooperative spectrum leasing systems. Finally, the simulation results confirm accuracy of our the analysis of the queueing stability.

APPENDIX
PROOF OF PROPOSITION 1

Assuming that the cooperative matching $X_{DWWRS-MAS}$ produced by our DWWRS-MAS is blocked by a blocking pair (PT_i, ST_m), we have $P_{ST}(i, m) < P_{ST}[I^*(m), m]$, where $PT_{I^*(m)}$ is the current cooperative partners of ST_m in the cooperative matching $X_{DWWRS-MAS}$. Based on our DWWRS-MAS, PT_i first discovers its cooperative partner with the aid of lowest transmit power $P_{PT}(i) = P_{p_1}$. If PT_i fails to find a cooperative partner at the power of P_{p_1}, it repeats the discovery procedure by increasing its power to the next higher power level, as seen in Table 1. Hence, according to the definition of blocking pair, PT_i first selects ST_m as its cooperative partner at the lower power, but ST_m intends to provide cooperative transmission assistance for another PT $PT_{I^*(m)}$ for the sake of minimizing its transmit power, namely $P_{ST}(i, m) > P_{ST}[I^*(m), m]$. Hence PT_i has to increase its power in order to form a cooperative pair $\mathcal{O}(PT_i, ST_{M^*(i)})$ based on cooperative matching $X_{DWWRS-MAS}$, as designed by our DWWRS-MAS of Section III. However, this contradicts the assumption of $P_{ST}(i, m) < P_{ST}[I^*(m), m]$. Hence, (PT_i, ST_m) cannot be a blocking pair. According to the objective functions of PT, none of the matched PTs would become a blocking individual, because an increased power is required for successfully conveying its data to the destination without cooperative transmission assistance. Furthermore, based on our DWWRS-MAS, a ST cannot be granted a transmission opportunity within the licensed spectrum if it is not matched to a PT. Therefore, no blocking pairs and/or blocking individuals are part of the cooperative matching $X_{DWWRS-MAS}$, which implies that our DWWRS-MAS is capable of producing a stable cooperative matching $X_{DWWRS-MAS}$.

REFERENCES

[1] W. C. Ao and K.-C. Chen, "Cognitive radio-enabled network-based cooperation: From a connectivity perspective," *IEEE J. Sel. Areas Commun.*, vol. 30, no. 10, pp. 1969–1982, Nov. 2012.

[2] Q. Ni and C. C. Zarakovitis, "Nash bargaining game theoretic scheduling for joint channel and power allocation in cognitive radio systems," *IEEE J. Sel. Areas Commun.*, vol. 30, no. 1, pp. 70–81, Jan. 2012. AQ:3

[3] Q. Zhao and B. M. Sadler, "A survey of dynamic spectrum access," *IEEE Signal Process. Mag.*, vol. 24, no. 3, pp. 79–89, May 2007.

[4] O. Simeone, I. Stanojev, S. Savazzi, Y. Bar-Ness, U. Spagnolini, and R. Pickholtz, "Spectrum leasing to cooperating secondary ad hoc networks," *IEEE J. Sel. Areas Commun.*, vol. 26, no. 1, pp. 203–213, Jan. 2008.

[5] L. L. Hanzo, Y. Akhtman, L. Wang, and M. Jiang, *MIMO-OFDM for LTE, WiFi and WiMAX: Coherent Versus Non-Coherent and Cooperative Turbo Transceivers*. New York, NY, USA: IEEE Press, 2010.

[6] X. Bao, P. Martins, T. Song, and L. Shen, "Stable throughput and delay performance in cognitive cooperative systems," *IET Commun.*, vol. 5, no. 2, pp. 190–198, Jan. 2011.

[7] Y. Zou, Y.-D. Yao, and B. Zheng, "Diversity-multiplexing tradeoff in selective cooperation for cognitive radio," *IEEE Trans. Commun.*, vol. 60, no. 9, pp. 2467–2481, Sep. 2012.

[8] Y. Cao, T. Jiang, C. Wang, and L. Zhang, "CRAC: Cognitive radio assisted cooperation for downlink transmissions in OFDMA-based cellular networks," *IEEE J. Sel. Areas Commun.*, vol. 30, no. 9, pp. 1614–1622, Oct. 2012.

[9] T. Luan, F. Gao, and X.-D. Zhang, "Joint resource scheduling for relay-assisted broadband cognitive radio networks," *IEEE Trans. Wireless Commun.*, vol. 11, no. 9, pp. 3090–3100, Sep. 2012.

[10] M. Xia and S. Aissa, "Cooperative AF relaying in spectrum-sharing systems: Outage probability analysis under co-channel interferences and relay selection," *IEEE Trans. Commun.*, vol. 60, no. 11, pp. 3252–3262, Nov. 2012.

[11] X. Wang, K. Ma, Q. Han, Z. Liu, and X. Guan, "Pricing-based spectrum leasing in cognitive radio networks," *IET Netw.*, vol. 1, no. 3, pp. 116–125, Sep. 2012.

[12] S. K. Jayaweera, M. Bkassiny, and K. A. Avery, "Asymmetric cooperative communications based spectrum leasing via auctions in cognitive radio networks," *IEEE Trans. Wireless Commun.*, vol. 10, no. 8, pp. 2716–2724, Aug. 2011.

[13] I. Stanojev, O. Simeone, U. Spagnolini, Y. Bar-Ness, and R. L. Pickholtz, "Cooperative ARQ via auction-based spectrum leasing," *IEEE Trans. Commun.*, vol. 58, no. 6, pp. 1843–1856, Jun. 2010.

[14] J. Feng, R. Zhang, and L. Hanzo, "A spectrum leasing cooperative medium access protocol and its stability analysis," *IEEE Trans. Veh. Technol.*, vol. 61, no. 8, pp. 3718–3730, Oct. 2012.

[15] T. Elkourdi and O. Simeone, "Spectrum leasing via cooperation with multiple primary users," *IEEE Trans. Veh. Technol.*, vol. 61, no. 2, pp. 820–825, Feb. 2012.

[16] S. Bayat, R. H. Y. Louie, Y. Li, and B. Vucetic, "Cognitive radio relay networks with multiple primary and secondary users: Distributed stable matching algorithms for spectrum access," in *Proc. IEEE Int. Conf. Commun. (ICC)*, Kyoto, Japan, Jun. 2011, pp. 1–6.

[17] N. Namvar and F. Afghah, "Spectrum sharing in cooperative cognitive radio networks: A matching game framework," in *Proc. 49th Annu. Conf. Inf. Sci. Syst. (CISS)*, Baltimore, MD, USA, Mar. 2015, pp. 1–5.

[18] D. Li, Y. Xu, X. Wang, and M. Guizani, "Coalitional game theoretic approach for secondary spectrum access in cooperative cognitive radio networks," *IEEE Trans. Wireless Commun.*, vol. 10, no. 3, pp. 844–856, Mar. 2011.

[19] M. Shamaiah, S. H. Lee, S. Vishwanath, and H. Vikalo, "Distributed algorithms for spectrum access in cognitive radio relay networks," *IEEE J. Sel. Areas Commun.*, vol. 30, no. 10, pp. 1947–1957, Nov. 2012.

[20] L. A. Maglaras and D. Katsaros, "Layered backpressure scheduling for delay reduction in ad hoc networks," in *Proc. IEEE Int. Symp. World Wireless, Mobile Multimedia Netw. (WoWMoM)*, Jun. 2011, pp. 1–5.

[21] D. Chase, "Digital signal design concepts for a time-varying Rician channel," *IEEE Trans. Commun.*, vol. 24, no. 2, pp. 164–172, Feb. 1976.

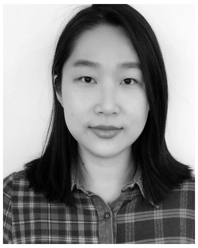
[22] D. Gusfield and R. W. Irving, *The Stable Marriage Problem: Structure and Algorithms*. Cambridge, U.K.: Cambridge Univ. Press, 1989.

[23] M. Zukerman. (2008). *Introduction to Queueing Theory and Stochastic Teletraffic Models*. [Online]. Available: http://www.mendeley.com/catalog/introduction-queueing-theory-stochastic-teletraffic-models-1/

[24] A. A. El-Sherif, A. K. Sadek, and K. J. R. Liu, "Opportunistic multiple access for cognitive radio networks," *IEEE J. Sel. Areas Commun.*, vol. 29, no. 4, pp. 704–715, Apr. 2011.

[25] R. M. Loynes, "The stability of a queue with non-independent inter-arrival and service times," *Math. Proc. Camb. Philos. Soc.*, vol. 58, no. 3, pp. 497–520, Jul. 1962.

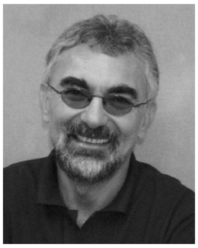
JIAO FENG received the B.Eng. and M.Sc. degrees in communications engineering from Jilin University, Jilin, China, in 2007 and 2009, respectively, and the Ph.D. degree in wireless communications from the University of Southampton, U.K., in 2014. Since 2014, she has been with the School of Electric & Information Engineering, Nanjing University of Information Science & Technology, China. She is involved in the projects sponsored by the National Natural Science Foundation and by the Natural Science Foundation of Jiangsu. Her research interests include co-operative communication, network protocols, cognitive radio network, and matching theory.



WEI LIANG received the M.Sc. and Ph.D. degrees in wireless communication from the University of Southampton, Southampton, U.K., in 2010 and 2015, respectively. She is currently a Post-Doctoral Research Fellow with Lancaster University. Her research interests include adaptive coded modulation, network coding, matching theory, game theory, cooperative communication, cognitive radio network, and non-orthogonal multiple access scheme.

SOON XIN NG received the B.Eng. degree (Hons.) in electronics engineering and the Ph.D. degree in wireless communications from the University of Southampton, Southampton, U.K., in 1999 and 2002, respectively. From 2003 to 2006, he was a Post-Doctoral Research Fellow, where he was involved in collaborative European research projects such as SCOUT, NEWCOM, and PHOENIX. Since 2006, he has been a member of academic staff with the School of Electronics and Computer Science, University of Southampton. He is involved in the OPTIMIX and CONCERTO European projects as well as the IUATC and UC4G projects. He is currently an Associate Professor of Telecommunications with the University of Southampton. He has authored over 180 papers and co-authored two John Wiley/IEEE Press books in his research field.

His research interests include adaptive coded modulation, coded modulation, channel coding, space-time coding, joint source and channel coding, iterative detection, OFDM, MIMO, co-operative communications, distributed coding, quantum error correction codes, and joint wireless-and optical- fiber communications. He is a Chartered Engineer and a fellow of the Higher Education Academy, U.K.



LAJOS HANZO received the master's degree in electronics, the Ph.D. degree, and the Doctor Honoris Causa degree from the Technical University of Budapest, in 1976, 1983, and 2009, respectively, and the Doctor Honoris Causa degree from the University of Edinburgh in 2015. During his 40-year career in telecommunications, he has held various research and academic positions in Hungary, Germany, and the U.K. Since 1986, he has been with the School of Electronics and Computer Science, University of Southampton, U.K., as the Chair in Telecommunications. He has successfully supervised 110 Ph.D. students, co-authored 20 John Wiley/IEEE Press books in mobile radio communications totaling in excess of 10 000 pages, co-authored over 1 600 research contributions found at the IEEE Xplore, acted as the TPC Chair and General Chair of the IEEE conferences, presented keynote lectures, and received a number of distinctions. He is directing a 60 strong academic research team, involved in a range of research projects in the field of wireless multimedia communications sponsored by the industry, the Engineering and Physical Sciences Research Council, U.K., the European Research Councils Advanced Fellow Grant, and the Royal Societies Wolfson Research Merit Award. He is an enthusiastic supporter of industrial and academic liaison and offers a range of industrial courses.

He is also a fellow of the Royal Academy of Engineering, the Institution of Engineering and Technology, and the European Association for Signal Processing. He is a Governor of the IEEE ComSoc and of VTS. From 2008 to 2012, he was the Editor-in-Chief of the IEEE Press and a Chaired Professor with Tsinghua University, Beijing. He has 25 000+ citations.

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