Distributed Algorithm for Multiple Antenna Cooperative Cognitive Radio Networks with Multiple Primary and Secondary Users

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Abstract— We propose a distributed spectrum access algorithm for cognitive radio relay networks with multiple primary users (PU) and multiple secondary users (SU) utilizing multiple antennas at their transmitter. The overlay model is considered, where the PUs allow spectrum access opportunities for the SUs, in exchange for the SUs cooperatively relaying the PUs' data in exchange for both spectrum access and monetary compensation. We show that the PUs which utilize the SUs for cooperative relaying achieves a rate greater than what it would achieve without cooperative relaying, i.e., direct transmission, and thus motivates their participation in the proposed algorithm.

1. INTRODUCTION

Cognitive radio has been proposed as a promising technology to improve the spectral efficiency. This is achieved by allowing unlicensed secondary users (SU) to coexist with licensed primary users (PU) in the same spectrum. This coexistence is facilitated by spectrum access techniques, such as those involving an agreement between the PUs and SUs on an acceptable spectrum access strategy. The key idea is that the PUs are motivated to lease spectrum bands to the SUs in exchange for some form of compensation.

Monetary compensation have been well studied (see e.g., [1–3]), with the predominant approach for spectrum access and performance analysis involving the use of tools from game theory. For these monetary payment schemes, the PUs are assumed to have sufficient spectrum for leasing to the SUs, such that their own performance requirements are not affected. In practice, however, the PUs may desire higher data rates than what its current spectrum can provide.

Multiple antenna technology is well known as a powerful technique to enhance performance, due to their ability to provide diversity, high reliability and capacity in wireless networks. To allow for higher data rates, the use of cooperative relaying has emerged as a powerful technique due to its ability to exploit user diversity and provide high reliability and capacity in wireless networks [4]. This is achieved by the use of intermediate relay nodes to aid transmission between the source and destination nodes. The use of cooperative relaying is particularly advantageous when the direct link between the source and destination is weak, due to, for example, high shadowing.

This paper is organized as follows. In Section 2, we first describe our system model. We then formulate the problem we are trying to solve in Section 3, and present a distributed solution to this problem in Section 4. Finally, we analyze the performance and the implementation aspects of our proposed algorithm in Section 5.

2. SYSTEM MODEL AND UTILITY SETTING

We consider an overlay cognitive radio wireless network, comprising of L_{PU} PU transmitter $\{\mathrm{PT}_i\}_{i=1}^{L_{\mathrm{PU}}}$ -PU receiver $\{\mathrm{PR}_i\}_{i=1}^{L_{\mathrm{PU}}}$ pairs, with the ℓth pair having a rate requirement of $R_{\mathrm{PU}_\ell,\mathrm{req}}$, and with each pair occupying a unique spectrum band of constant size. In the same network, there are L_{SU} SU transmitter $\{\mathrm{ST}_i\}_{i=1}^{L_{\mathrm{SU}}}$–SU receiver $\{\mathrm{SR}_i\}_{i=1}^{L_{\mathrm{SU}}}$ pairs, with the qth pair having a rate requirement of $R_{\mathrm{SU}_q,\mathrm{req}}$, and seeking to obtain access to one spectrum band occupied by a (PT, PR) pair. The secondary transmitters all are equipped with N antennas and the other transmitters and receivers are equipped with single antenna. We assume that there are T time slots per transmission frame, and each (ST, SR) pair has access to a monetary value C.

Each PT attempts to grant spectrum access to a unique (ST, SR) pair, as determined by the various matching algorithms, in exchange for (i) the ST cooperatively relaying the PT's data to the corresponding PR, and (ii) monetary compensation. In particular, without loss of generality (w.l.o.g), let us consider $(\mathrm{PT}_\ell, \mathrm{PR}_\ell)$, whose transmission is relayed by ST_q during a fraction $\beta_{\ell,q}$ $(0 \leq \beta_{\ell,q} \leq 1)$ of T, whilst also receiving a fraction $\zeta_{\ell,q}$ $(0 \leq \zeta_{\ell,q} \leq 1)$ of C from ST_q, as depicted

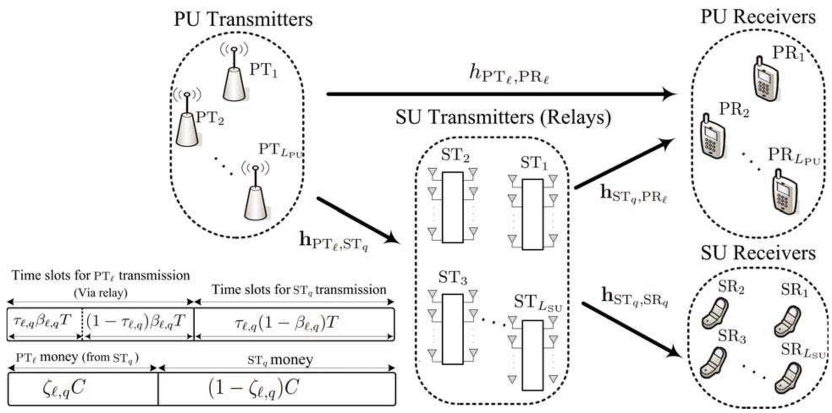


Figure 1: Secondary user and primary user spectrum-access model. The channel and price and time slot allocation numbers are indicated for $(\mathrm{PT}_\ell, \mathrm{PR}_\ell)$ and $(\mathrm{ST}_q, \mathrm{SR}_q)$.

in Fig. 1. We will refer to $\zeta_{\ell,q}$ and $\beta_{\ell,q}$ as the price and time slot allocation numbers respectively, whose exact values will be determined by the matching algorithms described in Section 3.

During the cooperative relaying stage in the initial $\beta_{\ell,q}T$ time slots, a fraction $\tau_{\ell,q}$ $(0 < \tau_{\ell,q} < 1)$ is first allocated for PT_ℓ to broadcast its signal to ST_q and PR_ℓ, thus occurring in the first $\beta_{\ell,q}\tau_{\ell,q}T$ time slots. In the subsequent $\beta_{\ell,q}(1-\tau_{\ell,q})T$ time slots, ST_q will beamforming the PT_ℓ's signal using maximum ratio transmission (MRT) and cooperatively relays the signal from ST_q to PR_ℓ.

PR_ℓ then applies maximum ratio combining (MRC) to the signal received from PT_ℓ in the first $\beta_{\ell,q}\tau_{\ell,q}T$ time slots, and the signal received from ST_q in the subsequent $\beta_{\ell,q}(1-\tau_{\ell,q})T$ time slots. After this cooperative relaying stage, PT_ℓ ceases transmission, allowing ST_q to beamform to SR_q over the spectrum occupied by (PT_ℓ, PR_ℓ) in the final $(1-\beta_{\ell,q})T$ time slots. The ST_q will beamforming its signal using maximum ratio transmission (MRT) and transmit the signal from ST_q to SR_q.

In particular, the received scalar signal from the PT_ℓ at the PR_ℓ in the time slot $\beta_{\ell,q}\tau_{\ell,q}T$ can be written as

$$y_{\mathrm{PR}_{\ell,1}} = \sqrt{P_{\mathrm{PT}_\ell}} h_{\mathrm{PT}_\ell,\mathrm{PR}_\ell} x_{\mathrm{PT}_\ell} + n_{\mathrm{PR}_{\ell,1}} \tag{1}$$

where P_{PT_ℓ} is the transmission power at PT_ℓ, $h_{\mathrm{PT}_\ell,\mathrm{PR}_\ell} \sim \mathcal{CN}(0, d_{\mathrm{PT}_\ell,\mathrm{PR}_\ell}^{-\alpha})$ is the Rayleigh channel from PT_ℓ to PR_ℓ, α is the path loss exponent, $d_{\mathrm{PT}_\ell,\mathrm{PR}_\ell}$ is the distance from PT_ℓ to PR_ℓ, x_{PT_ℓ} is the transmitted scalar symbol from the PT_ℓ with $\mathrm{E}[|x_{\mathrm{PT}_\ell}|] = 1$, $n_{\mathrm{PR}_{\ell,1}} \sim \mathcal{CN}(0, \sigma^2)$ is additive white Gaussian noise (AWGN) at the PR_ℓ and σ^2 is the noise variance.

At the ST_q, after applying a $1 \times N$ weight vector $\mathbf{w}_r^\dagger$ to the received signal from the PT_ℓ, the resultant scalar signal at the ST_q in the $\beta_{\ell,q}\tau_{\ell,q}T$ time slot can be written as

$$y_{\mathrm{ST}_q} = \sqrt{P_{\mathrm{PT}_\ell}} \mathbf{w}_r^\dagger \mathbf{h}_{\mathrm{PT}_\ell,\mathrm{ST}_q} x_{\mathrm{PT}_\ell} + \mathbf{w}_r^\dagger \mathbf{n}_{\mathrm{ST}_q} \tag{2}$$

where $\mathbf{h}_{\mathrm{PT}_\ell,\mathrm{ST}_q} \sim \mathcal{CN}_{N\times 1}(0, d_{\mathrm{PT}_\ell,\mathrm{ST}_q}^{-\alpha}\mathbf{I}_N)$ is the Rayleigh channel vector from the PT_ℓ to ST_q, $d_{\mathrm{PT}_\ell,\mathrm{ST}_q}$ is the distance from PT_ℓ to ST_q, $\mathbf{n}_{\mathrm{ST}_q}$ is additive white Gaussian noise (AWGN) at the ST_q and $(.)^\dagger$ denotes conjugate transpose.

In the subsequent $\beta_{\ell,q}(1-\tau_{\ell,q})T$ time slot, the ST_q first normalizes the received PT_ℓ's signal by multiplying (2) by the normalization constant $g_{\mathrm{ST}}^{\ell,q} = 1/\sqrt{\mathbf{w}_r^\dagger (P_{\mathrm{PT}_\ell} \mathbf{h}_{\mathrm{PT}_\ell,\mathrm{ST}_q} \mathbf{h}_{\mathrm{PT}_\ell,\mathrm{ST}_q}^\dagger + \sigma^2 \mathbf{I}_N) \mathbf{w}_r}$.

The ST_q then amplifies and forwards the normalized signal $g_{\mathrm{ST}}^{\ell,q} y_{\mathrm{ST}_q}$. ST then applies a $N \times 1$ transmit weight vector $\mathbf{w}_{\mathrm{PU}}$ to the normalized PT's signal. The received scalar signal at the PR_ℓ from the ST_q can thus be written as

$$y_{\mathrm{PR}_{\ell,2}} = g_{\text{ST-PR}}^{\ell,q} g_{\mathrm{ST}}^{\ell,q} \mathbf{h}^\dagger{}_{\mathrm{ST}_q,\mathrm{PR}_\ell} \mathbf{w}_{\mathrm{PU}} \mathbf{w}_r^\dagger \mathbf{h}_{\mathrm{PT}_\ell,\mathrm{ST}_q} x_{\mathrm{PT}_\ell} + g_{\text{ST-PR}}^{\ell,q} g_{\mathrm{ST}}^{\ell,q} \mathbf{h}^\dagger{}_{\mathrm{ST}_q,\mathrm{PR}_\ell} \mathbf{w}_{\mathrm{PU}} \mathbf{w}_r^\dagger \mathbf{n}_{\mathrm{ST}_q} + n_{\mathrm{PR}_{\ell,2}} \tag{3}$$

where $\mathbf{h}_{\mathrm{ST}_q,\mathrm{PR}_\ell} \sim \mathcal{CN}_{N\times 1}(\mathbf{0}, d_{\mathrm{ST}_q,\mathrm{PR}_\ell}^{-\alpha}\mathbf{I}_N)$ is the Rayleigh channel vector from ST_q to PR_ℓ, $d_{\mathrm{ST}_q,\mathrm{PR}_\ell}$ is the distance from ST_q to PR_ℓ, and $n_{\mathrm{PR}_{\ell,2}} \sim \mathcal{CN}(0, \sigma^2)$ is additive white Gaussian noise (AWGN) at the PR_ℓ. $g_{\text{ST-PR}}^{\ell,q}$ is the normalization constant, designed to ensure that the total transmit power at the ST_q is constrained, and is given by $g^{\ell,q}_{\text{ST-PR}}=\sqrt{P_{\mathrm{ST}_q}/\mathrm{Trace}(\mathbf{w}_{\mathrm{PU}}\mathbf{w}^{\dagger}_{\mathrm{PU}})}$ where P_{ST_q} is the transmission power at ST_q.

In the time slot $\beta_{\ell,q}\tau_{\ell,q}T$ of the proposed scheme, the ST receives only the PT's signal, and thus the optimal linear weight design is MRC. The received weight $\mathbf{w}_r$ at the ST is thus chosen as $\mathbf{w}_r = \frac{\mathbf{h}_{\mathrm{PT}_\ell,\mathrm{ST}_q}}{\|\mathbf{h}_{\mathrm{PT}_\ell,\mathrm{ST}_q}\|}$ where $\|.\|$ denotes the Frobenius norm. In the time slot $\beta_{\ell,q}(1-\tau_{\ell,q})T$, the ST amplifies and forwards the PT's signal. The transmit weight $\mathbf{w}_{\mathrm{PU}}$ at the ST is chosen according to the principles of MRT as $\mathbf{w}_{\mathrm{PU}} = \frac{\mathbf{h}_{\mathrm{ST}_q,\mathrm{PR}_\ell}}{\|\mathbf{h}_{\mathrm{ST}_q,\mathrm{PR}_\ell}\|}$.

The received scalar signal at the SR_q from the ST_q in the $(1-\beta_{\ell,q})T$ time slot can be written as

$$y_{\mathrm{SR}_q} = g^{\ell,q}_{\text{ST-SR}}\mathbf{h}^{\dagger}{}_{\mathrm{ST}_q,\mathrm{SR}_q,\ell}\mathbf{w}_{\mathrm{SU}}x_{\mathrm{ST}_q} + n_{\mathrm{SR}_q} \tag{4}$$

where $\mathbf{w}_{\mathrm{SU}}$ is the $N\times 1$ transmit weight vector, $\mathbf{h}_{\mathrm{ST}_q,\mathrm{SR}_q,\ell} \sim \mathcal{CN}_{N\times 1}(\mathbf{0}, d^{-\alpha}_{\mathrm{ST}_q,\mathrm{SR}_q}\mathbf{I}_N)$ is the Rayleigh channel vector from ST_q to SR_q while using the PT_ℓ's spectrum, $d_{\mathrm{ST}_q,\mathrm{SR}_q}$ is the distance from ST_q to SR_q, and $n_{\mathrm{SR}_q} \sim \mathcal{CN}(0,\sigma^2)$ is additive white Gaussian noise (AWGN) at the SR_q. $g^{\ell,q}_{\text{ST-SR}}$ is the normalization constant, designed to ensure that the total transmit power at the ST_q is constrained, and is given by $g^{\ell,q}_{\text{ST-SR}}=\sqrt{P_{\mathrm{ST}_q}/\mathrm{Trace}(\mathbf{w}_{\mathrm{SU}}\mathbf{w}^{\dagger}_{\mathrm{SU}})}$.

The transmit weight $\mathbf{w}_{\mathrm{SU}}$ at the ST is chosen according to MRT as $\mathbf{w}_{\mathrm{SU}} = \frac{\mathbf{h}_{\mathrm{ST}_q,\mathrm{SR}_q}}{\|\mathbf{h}_{\mathrm{ST}_q,\mathrm{SR}_q}\|}$. The PR_ℓ then applies MRC to the two received signals, given in (1) and (4) in the first and second time slot respectively, resulting in a received signal to interference noise ratio (SINR) at the PR_ℓ given by

$$\gamma_{\mathrm{PR}_{\ell,q}} = \frac{P_{\mathrm{PT}_\ell}|h_{\mathrm{PT}_\ell,\mathrm{PR}_\ell}|^2}{\sigma^2} + \frac{\gamma_1\gamma_2}{\gamma_1+\gamma_2+1} \tag{5}$$

where $\gamma_1 = \frac{P_{\mathrm{PT}_\ell}|\mathbf{h}_{\mathrm{PT}_\ell,\mathrm{ST}_q}|^2}{\sigma^2}$ and $\gamma_2 = \frac{{g^{\ell,q}_{\text{ST-PR}}}^2 {g^{\ell,q}_{\text{ST}}}^2\|\mathbf{h}_{\mathrm{ST}_q,\mathrm{PR}_\ell}\|^4\|\mathbf{h}_{\mathrm{PT}_\ell,\mathrm{ST}_q}\|^4}{{g^{\ell,q}_{\text{ST-PR}}}^2 {g^{\ell,q}_{\text{ST}}}^2\|\mathbf{h}_{\mathrm{ST}_q,\mathrm{PR}_\ell}\|^4|\mathbf{h}^{\dagger}_{\mathrm{PT}_\ell,\mathrm{ST}_q}|^2+\sigma^2}$ and the received signal to interference noise ratio (SINR) at the SR_q given by $\gamma_{\mathrm{SR}_{\ell,q}} = \frac{{g^{\ell,q}_{\text{ST-SR}}}^2\|\mathbf{h}_{\mathrm{ST}_q,\mathrm{SR}_q,\ell}\|^2}{\sigma^2}$.

Note that the PRs requires $h_{\mathrm{PT}_\ell,\mathrm{PR}_\ell}$ and $g^{\ell,q}_{\text{ST-PR}}g^{\ell,q}_{\text{ST}}\mathbf{h}^{\dagger}{}_{\mathrm{ST}_q,\mathrm{PR}_\ell}\mathbf{w}_{\mathrm{PU}}\mathbf{w}^{\dagger}_r\mathbf{h}_{\mathrm{PT}_\ell,\mathrm{ST}_q}x_{\mathrm{PT}_\ell}$ to perform MRC at PR. $h_{\mathrm{PT}_\ell,\mathrm{PR}_\ell}$ can be obtained via pilot training symbols [5], and the complex scalar $g^{\ell,q}_{\text{ST-PR}}g^{\ell,q}_{\text{ST}}\mathbf{h}^{\dagger}{}_{\mathrm{ST}_q,\mathrm{PR}_\ell}\mathbf{w}_{\mathrm{PU}}\mathbf{w}^{\dagger}_r\mathbf{h}_{\mathrm{PT}_\ell,\mathrm{ST}_q}x_{\mathrm{PT}_\ell}$, is initially transmitted from the ST before the transmission procedure.

In practice, channel state information (CSI) between the ST and SR can be obtained by the classic channel training, estimation, and feedback mechanisms as in [5], while the CSI between the PT and ST and the ST and PR can be obtained as in [6], as we assume that the PU and SU systems cooperate with each other. Finally, in a fading environment, there might be cases where it is difficult for the ST to perfectly estimate instantaneous channels. In such cases,the results obtained in this paper provide upper-bounds for the performance of the proposed scheme in a CR network.

In this paper, we consider the amplify-and-forward (AF) relaying protocol, due to its simple and practical operation, and thus set $\tau_{\ell,q} = \frac{1}{2}$. We note, however, that the proposed algorithm is applicable to any relaying protocol, such as the decode-and-forward or compress-and-forward protocol. The AF gain at ST_q is chosen such that its instantaneous transmission power is constrained to P_{SU_q}.

To evaluate the performance of each $(\mathrm{PT},\mathrm{PR})$ and $(\mathrm{ST},\mathrm{SR})$ pair, we consider the utility function, which comprises of both rate and monetary factors. Specifically, for $(\mathrm{PT}_\ell,\mathrm{PR}_\ell)$, the achievable instantaneous rate is given by [4]

$$R_{\mathrm{PU}_{\ell,q}}(\beta_{\ell,q}) = \frac{\beta_{\ell,q}T}{2}\log_2\left(1+\frac{P_{\mathrm{PT}_\ell}|h_{\mathrm{PT}_\ell,\mathrm{PR}_\ell}|^2}{\sigma^2}+\frac{\gamma_1\gamma_2}{\gamma_1+\gamma_2+1}\right) \tag{6}$$

To allow for both the rate and monetary value to be combined into one utility function, we introduce a variable $\bar{c}\in\mathbb{R}^+$, with unit defined as: rate per unit monetary value. We can thus express the utility for $(\mathrm{PT}_\ell,\mathrm{PR}_\ell)$ as

$$U_{\mathrm{PU}_{\ell,q}}(\beta_{\ell,q},\zeta_{\ell,q}) = R_{\mathrm{PU}_{\ell,q}}(\beta_{\ell,q}) + \bar{c}\,\zeta_{\ell,q}C\ . \tag{7}$$

For (ST_q, SR_q), the achievable instantaneous rate is given by

$$R_{\mathrm{SU}_{q,\ell}}(\beta_{\ell,q}) = (1-\beta_{\ell,q})T\log_2\left(1+\frac{{g_{\text{ST-SR}}^{\ell,q}}^2|\mathbf{h}_{\mathrm{ST}_q,\mathrm{SR}_q,\ell}|^4}{\|\mathbf{h}_{\mathrm{ST}_q,\mathrm{SR}_q,\ell}\|\sigma^2}\right) \tag{8}$$

The utility for (ST_q, SR_q) is thus given by

$$U_{\mathrm{SU}_{q,\ell}}(\beta_{\ell,q},\zeta_{\ell,q}) = R_{\mathrm{SU}_{q,\ell}}(\beta_{\ell,q}) - \bar{k}\zeta_{\ell,q}C \tag{9}$$

where $\bar{k}\in\mathbb{R}^+$ is a variable which is defined to allow for both the rate and monetary value to be combined into one utility function, with unit defined as:rate per unit monetary value.

3. PROBLEM FORMULATION

In this section, we describe the optimization problem we aim to address. To proceed, we introduce some notation. We first define the primary and secondary user sets respectively as $\mathcal{P}=\{\mathrm{PU}_\ell=(\mathrm{PT}_\ell,\mathrm{PR}_\ell)\}_{\ell=1}^{L_{\mathrm{PU}}}$ and $\mathcal{S}=\{\mathrm{SU}_q=(\mathrm{ST}_q,\mathrm{SR}_q)\}_{q=1}^{L_{\mathrm{SU}}}$. Moreover, we define a $L_{\mathrm{PU}}\times L_{\mathrm{SU}}$ matching matrix $\mathbf{M}$, with $m_{i,j}=1$ if PU_i is matched with SU_j, and $m_{i,j}=0$ otherwise, where the notation $x_{i,j}$ denotes the (i,j)th entry of matrix $\mathbf{X}$. From this matrix, we introduce an injective function $\mu:(\mathcal{P}\cup\mathcal{S})\to(\mathcal{P}\cup\mathcal{S}\cup\{\varnothing\})$, such that (a) $\mu(\mathrm{PU}_\ell)\in(\mathcal{S}\cup\{\varnothing\})$, (b) $\mu(\mathrm{SU}_q)\in(\mathcal{P}\cup\{\varnothing\})$, and (c) $\mu(\mathrm{SU}_q)=\mathrm{PU}_\ell$ and $\mu(\mathrm{PU}_\ell)=\mathrm{SU}_q$ if $m_{\ell,q}=1$, for $\ell=1,\dots,L_{\mathrm{PU}}$ and $q=1,\dots,L_{\mathrm{SU}}$, (d) $\mu(\mathrm{SU}_q)=\varnothing$ if $m_{\ell,q}=0$, for $\ell=1,\dots,L_{\mathrm{PU}}$, and (e) $\mu(\mathrm{PU}_\ell)=\varnothing$ if $m_{\ell,q}=0$, for $q=1,\dots,L_{\mathrm{SU}}$.

We also define an $L_{\mathrm{PU}}\times L_{\mathrm{SU}}$ price allocation matrix $\mathbf{G}$ with $g_{i,j}=\zeta_{i,j}$, and an $L_{\mathrm{PU}}\times L_{\mathrm{SU}}$ time-slot allocation matrix $\mathbf{B}$ with $b_{i,j}=\beta_{i,j}$, and where $g_{i,j}=b_{i,j}=0$ if $m_{i,j}=0$. We denote the price and time-slot allocation matrices with continuous elements as $\mathbf{G}^{\mathrm{cont}}$ and $\mathbf{B}^{\mathrm{cont}}$ respectively. Mathematically, this implies that the elements of $\mathbf{G}^{\mathrm{cont}}$ and $\mathbf{B}^{\mathrm{cont}}$ respectively take values from the sets $\{g_{i,j}^{\mathrm{cont}}=\zeta_{i,j}\in\mathbb{R}:0\le\zeta_{i,j}\le1\}$ and $\{b_{i,j}^{\mathrm{cont}}=\beta_{i,j}\in\mathbb{R}:0\le\beta_{i,j}\le1\}$. So our problem here is a matching between $\mathcal{P}$ and $\mathcal{S}$ such that for each primary and secondary user is to ensure their minimum rate requirements are satisfied. When this is achieved, the secondary goal is to maximize their utility functions. To address these issues, we propose a distributed low-complexity algorithm which accounts for selfish users.

4. PROPOSED DISTRIBUTED MATCHING ALGORITHM

In this section, we describe the proposed algorithm which determines spectrum access for each $(\mathrm{PT},\mathrm{PR})$ and $(\mathrm{ST},\mathrm{SR})$ pair.

We first describe two scenarios we will be considering in the proposed algorithm, characterized by different assumptions on the received SNR at the transmitters and receivers.

4.1. Complete Received SNR

In the first scenario, PT_ℓ has perfect knowledge of the instantaneous receivedSNRs in $\{\frac{\gamma_{\mathrm{PT}_\ell}|h_{\mathrm{PT}_\ell,\mathrm{PR}_\ell}|^2}{d^\alpha_{\mathrm{PT}_\ell,\mathrm{PR}_\ell}}\}$, $\{\frac{\gamma_{\mathrm{PT}_\ell}|\mathbf{h}_{\mathrm{PT}_\ell,\mathrm{ST}_q}|^2}{d^\alpha_{\mathrm{PT}_\ell,\mathrm{ST}_q}}\}$, $\{\frac{\gamma_{\mathrm{ST}_q}|\mathbf{h}_{\mathrm{ST}_q,\mathrm{PR}_\ell}|^2}{d^\alpha_{\mathrm{ST}_q,\mathrm{PR}_\ell}}\}_{q=1}^{L_{\mathrm{SU}}}$. Moreover, ST_q has perfect knowledge of the instantaneous received SNRs in the expressions $\{\frac{\gamma_{\mathrm{ST}_q}|\mathbf{h}_{\mathrm{ST}_q,\mathrm{SR}_q,\ell}|^2}{d^\alpha_{\mathrm{ST}_q,\mathrm{SR}_q}}\}_{\ell=1}^{L_{\mathrm{PU}}}$. As such, PT_ℓ and ST_q are able to respectively calculate their *instantaneous* rate in (6) and (8).

4.2. Partial Received SNR

In the second scenario, PT_ℓ has knowledge of the average received SNRs in the term $\{\frac{\gamma_{\mathrm{ST}_q}}{d^\alpha_{\mathrm{ST}_q,\mathrm{PR}_\ell}}\}_{q=1}^{L_{\mathrm{SU}}}$ and the instantaneous received SNRs in the terms $\{\frac{\gamma_{\mathrm{PT}_\ell}|h_{\mathrm{PT}_\ell,\mathrm{PR}_\ell}|^2}{d^\alpha_{\mathrm{PT}_\ell,\mathrm{PR}_\ell}},\frac{\gamma_{\mathrm{PT}_\ell}|\mathbf{h}_{\mathrm{PT}_\ell,\mathrm{ST}_q}|^2}{d^\alpha_{\mathrm{PT}_\ell,\mathrm{ST}_q}}\}_{q=1}^{L_{\mathrm{SU}}}$. Moreover, ST_q has perfect knowledge of the instantaneous received SNRs in the term $\{\frac{\gamma_{\mathrm{ST}_q}|\mathbf{h}_{\mathrm{ST}_q,\mathrm{SR}_q,\ell}|^2}{d^\alpha_{\mathrm{ST}_q,\mathrm{SR}_q}}\}_{\ell=1}^{L_{\mathrm{PU}}}$. As such, PT_ℓ is able to calculate its instantaneous conditional rate, given by the expectation of the rate in (6) with respect to $\{\mathbf{h}_{\mathrm{PT}_\ell,\mathrm{ST}_q}\}_{q=1}^{L_{\mathrm{SU}}}$, while ST_q is able to calculate its *instantaneous* rate in (8).

4.3. Users Preference Lists

Each PT has a preference list of STs which can cooperatively relay the PT's message such that it obtains a rate greater than its minimum rate requirement.

Similarly, each ST has a preference list of PTs which, if it transmits in the spectrum band occupied by the (PT, PR) pair in the list, obtains a rate greater than its minimum rate requirement and a utility greater or equal to zero.

4.4. Proposed Algorithm

The key idea of the proposed algorithm is that each (PT, PR) pair trades with the (ST, SR) pair which provides the highest utility, through both cooperative relaying and monetary payment. This trading will be done by negotiating on the price and time-slot allocation numbers $\{\zeta_{\ell,q}, \beta_{\ell,q}\}_{\ell=1}^{L_{\mathrm{PU}}}{}_{q=1}^{L_{\mathrm{SU}}}$. We say PT_ℓ makes an *offer* of $(\zeta_{\ell,q}, \beta_{\ell,q})$ to ST_q to imply that PT_ℓ is willing to allow ST_q to transmit, in exchange for ST_q (i) cooperatively relaying PT_ℓ's message with time slot allocation number $\beta_{\ell,q}$ and, (ii) providing a monetary payment with price allocation number $\zeta_{\ell,q}$.

To summarize the main algorithm (MA), each PT will first make an offer to the ST which is first in its preference list. The ST will then check if the offering PT is in it's preference list. If it is, and the ST is already matched with another PT, the ST has two choices: (a) if the offering PT can provide a better utility than the ST's current matching, then the ST will reject its current matching in favor of the new matching,or (b) if the offering PT can not provide a better utility than the ST's current matching, the ST will reject the PT's offer. If the ST is not matched, then the ST will be matched with the offering PT. If the offering PT is not in the ST's preference list, the ST will reject the offering PT. The algorithm will then repeat this procedure with each PT until no more matchings are possible.

Note that if the ST rejects a PT, then PT updates its proposal, and the PT will either (i) decrease its price allocation number by a price step number δ, or (ii) decrease its time slot allocation number by a time slot-step number ϵ, depending on which option maximizes the PT's utility, and assuming a positive price and time-slot allocation number and the minimum data rate requirement for the PT is satisfied.

5. PERFORMANCE AND IMPLEMENTATION ANALYSIS

We now analyze the performance of the proposed algorithm, and consider related implementation issues. We first present some assumptions we will be considering in the analysis. To demonstrate that the (PT, PR) pairs are motivated to participate in the proposed algorithm, we set the minimum rate requirement of each (PT, PR) pair to be the rate of the direct PT to PR link. This is given for $(\mathrm{PT}_\ell, \mathrm{PR}_\ell)$ by $R_{\mathrm{PT}_\ell,\mathrm{PR}_\ell} = T\log_2(1+\frac{\gamma_{\mathrm{PT}_\ell}|h_{\mathrm{PT}_\ell,\mathrm{PR}_\ell}|^2}{d^{\alpha}_{\mathrm{PT}_\ell,\mathrm{PR}_\ell}})$ where $h_{\mathrm{PT}_\ell,\mathrm{PR}_\ell}$ and $d_{\mathrm{PT}_\ell,\mathrm{PR}_\ell}$ denote respectively the channel coefficient and distance from PT_ℓ to PR_ℓ. In this paper, we thus set $R_{\mathrm{PU}_\ell,\mathrm{req}} = R_{\mathrm{PT}_\ell,\mathrm{PR}_\ell}$.

5.1. Utility Performance

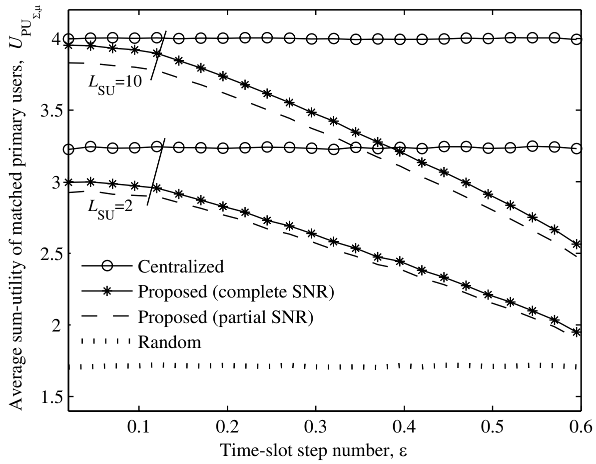
In fact, the proposed algorithm can achieve a utility for every matched (PT, PR) pair very close to the centralized optimal algorithm. This can be observed in Fig. 2(a), which plots the average sum-utility of all matched (PT, PR) pairs vs. time-slot step number ϵ for the proposed algorithm, the centralized algorithm, and the random algorithm. Note that the average sum-utility corresponds to the sum over all utilities achieved by the matched (PT, PR) pairs, averaged over the channel realizations, and given by $U_{\mathrm{PU}_\Sigma,\mu} = \sum_{\ell\in\mathcal{P}_\mu} \mathrm{E}[U_{\ell,\mu-\mathrm{ind}(\ell)}(\zeta_{\ell,\mu-\mathrm{ind}(\ell)}, \beta_{\ell,\mu-\mathrm{ind}(\ell)})]$, where $\mathcal{P}_\mu$ corresponds to all the (PT, PR) pairs matched under μ.

We first observe in Fig. 2(b) that for the proposed algorithm, the complete and partial received SNR scenarios achieve very similar performance, despite the different channel assumptions. We next observe that the proposed algorithm (i) achieves a sum-utility comparable with the sum-utility of the centralized algorithm for sufficiently small ϵ, and (ii) performs significantly better than the random matching algorithm.

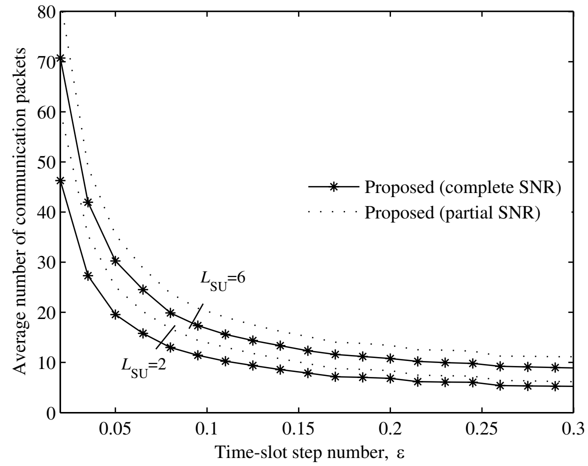
In practice, the unmatched PTs will transmit directly to their corresponding PRs and thus $(\mathrm{PT}_\ell, \mathrm{PR}_\ell)$ will achieve the rate $R_{\mathrm{PT}_\ell,\mathrm{PR}_\ell}$. However, the unmatched STs will not be able to transmit at all. To remedy this, various modifications to the proposed algorithm can be made, such as integrating a fairness mechanism into the algorithm so each ST has a turn transmitting, though at different times.

5.2. Overhead and Complexity

The proposed algorithm is distributed, and thus incurs significantly less overhead and complexity compared to centralized algorithms. It can be observed from the proposed algorithm that the total number of times the PTs communicates with the STs scales as



(a)



(b)

Figure 2: (a) Average sum-utility of all matched $(\mathrm{PT}, \mathrm{PR})$ pairs vs. time slot step-number ϵ. (b) Total number of communication packets vs. ϵ for the complete instantaneous received SNR scenario with $\zeta_{\text{init}} = 0.99$, $\beta_{\text{init}} = 0.99$, $\delta = \epsilon$, $\gamma_{\text{SU}_1} = \ldots \gamma_{\text{SU}_{L_{\text{SU}}}} = 25\,\text{dB}$, $L_{\text{PU}} = 2$, $\gamma_{\text{PU}_1} = \gamma_{\text{PU}_2} = 5\,\text{dB}$, $R_{\text{SU,req}} = 0.1$, $\{R_{\text{PU}_\ell,\text{req}} = R_{\text{PT}_\ell,\text{PR}_\ell}\}_{\ell=1}^{L_{\text{PU}}}$, $N = 2$, $\bar{c} = 1$, $\bar{k} = 1$ and $\alpha = 4$.

$$Q \sim L_{\text{PU}} L_{\text{SU}} \left(a \left\lfloor \frac{\zeta_{\text{init}}}{\delta} \right\rfloor + b \left\lfloor \frac{\beta_{\text{init}}}{\epsilon} \right\rfloor \right) \tag{10}$$

where $a, b \in \mathbb{R}^+$. We observe in (10) that the amount of overhead, and thus the number of iterations, decreases with ϵ and δ. We see that the total number of communication packets converge to a constant at sufficiently high ϵ. This is because if ϵ is sufficiently large, the time-slot allocation numbers are updated in the algorithm in such a way that the preference lists for each (PT, PR) and (ST, SR) pair remain unchanged.

We note that the packet length required for communication between the PTs and the STs is very short. In particular, assuming that ζ_{init}, β_{init}, δ and ϵ are initially known to all users, each PT is only required to send *one bit* to the first ST in its preference list indicating an offer, and the corresponding ST only needs to send *one bit* back to the offering PT indicating either acceptance or rejection. As demonstrated in Fig. 2(b), the total number of communication packets for each PT can be designed to be reasonably small, and thus given the short packet lengths, the total running time and amount of overhead from the proposed algorithm can be quite small.

6. CONCLUSION

We proposed a distributed algorithm for spectrum access which guarantees that the PUs' and SUs' rate requirement are satisfied. Numerical analysis also revealed that the distributed algorithm achieves a performance comparable to an optimal centralized algorithm, but with significantly less overhead and complexity.

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