Cooperative Amplify-and-Forward Relaying in Cognitive Radio Networks

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***Abstract*—In this paper, we consider an underlay cognitive radio network consisting of a primary transmitter (PT), a primary receiver (PR), a secondary transmitter (ST) and a secondary receiver (SR). We propose a two time slot spectrum sharing scheme based on cooperative relay transmission in addition to a practical design of the antenna weights at the ST to achieve high performance at the primary and the secondary networks. To analyze the performance of our proposed scheme, we first derive a closed form expression for the diversity order achieved at the PR and the SR. We then show through simulations that our proposed scheme, compared to conventional systems where no cooperation occurs, results in an improved quality of service at both the primary and the secondary networks, namely, the error rate and the ergodic capacity.**

I. Introduction

Cognitive radio (CR) [1] has been recently proposed as a promising technology to improve the utilization efficiency of radio spectrum [2]. It allows secondary user (SU) networks to coexist with primary user (PU) networks through spectrum sharing. A commonly used model in CR networks is the underlay model [3]. In this model, the SUs are allowed to simultaneously transmit with the PUs over the same spectrum provided, that its received signal power levels at all PUs receivers are kept below some predefined threshold known as the interference-temperature constraint [2].

Recently, cooperative communication has emerged as a powerful technique to exploit user diversity and provide significant gains in reliability and capacity of wireless networks. This is achieved by the use of intermediate relay nodes, which are used to aid transmission from the source to destination node. The two most common cooperation protocols are Decode and Forward (DF) and Amplify and Forward (AF). DF is a simple scheme, which decodes the signal at the relay and re-encodes it before forwarding it to the destination [4]. AF is a simpler scheme, in which the signal is simply amplified at the relay and forwarded to the destination [4]. In this work, we consider the use of the AF protocol, due to its simplicity.

The performance gains achieved by cooperative relaying has prompted its application to the spectrum sharing problem in CR networks. In particular, spectrum sharing is performed in [5] via a time-sharing scheme, where the PU may lease dedicated time slots for the SUs in exchange for the SUs cooperatively relaying the PU's data. In [6], spectrum sharing is performed by the SU simultaneously relaying the PU's data and its own data. However, these schemes considered the case where the PU controls the spectrum leasing process to guarantee or improve its own performance; a process which may not translate to performance guarantees for the SUs.

In this paper, we consider a CR network comprising of a primary transmitter (PT), primary receiver (PR) and a secondary receiver (SR), each equipped with a single antenna, and a secondary base station (ST) equipped with N antennas. We propose a two time slot spectrum sharing scheme, based on cooperative relay transmission using AF; this will result in a higher data rate and improved error performance for the PU and SU networks over practical SNR values and numbers of antennas, compared to conventional systems where no cooperation occurs. In this transmission scheme, the PT transmits its signal in the first time slot to the PR, SR and ST. In the second time slot, the PT remains silent while the ST simultaneously forwards the PT's signal to the PR and transmits its own signals to the SR. In order to achieve high performance at the PU and SU networks, we propose the design of antenna weights at the ST such that (i) the power of the signals intended for the PR and SR are maximized and (ii) the interfering signals from the ST and PT at the PR and SR, respectively, are cancelled. We verify the capacity and error performance gains of our design both analytically, by deriving the diversity order achieved at the PR and the SR, and numerically, through simulations.

The rest of this paper is organized as follows. In Section II, the system model and the proposed transmission scheme are introduced. The proposed design of the antenna weights at the ST is described in Section III. The system performance based on the proposed weights design is analyzed and evaluated in Section IV. Finally, conclusions are drawn in Section V.

II. System Model

We consider a two time slot transmission scheme as in Fig. 1, where in the first time slot, the PT sends its signal which is received by the PR, the ST and the SR. In the second time slot, the ST amplifies and forwards the PT's signal in addition to transmitting its own signal, while the PT remains silent. In this transmission scheme, the PR receives two independent copies of the signal transmitted by the PT, which are retrieved by applying a maximum ratio combining (MRC) of the received signals, over the two time slots. The ST's signal is retrieved at the SR by discarding the received signal from the PT in the first time slot and decoding the received signal from the ST in the second time slot transmission.

Digital Object Identifier: 10.4108/ICST.CROWNCOM2010.9260
http://dx.doi.org/10.4108/ICST.CROWNCOM2010.9260

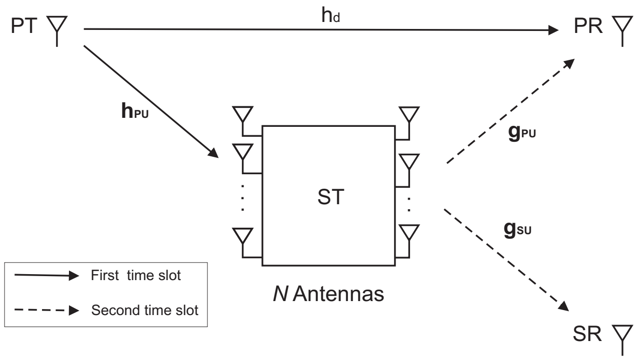

Fig. 1. System configuration

In the first time slot, the received signal from the PT at the PR can be written as

$$r_{\mathrm{PU},1} = \sqrt{P_{\mathrm{PU}}} h_d x_{\mathrm{PU}} + n_{\mathrm{PU}} \ , \quad (1)$$

where P_{PU} is the transmitted power from the PT, h_d is the channel coefficient from the PT to the PR, x_{PU} is the transmitted scalar data from the PT with $\mathrm{E}[|x_{\mathrm{PU}}|^2] = 1$, n_{PU} is the additive white Gaussian noise (AWGN) at the PT with $n_{\mathrm{PU}} \sim \mathcal{CN}(0, \sigma^2)$. After applying the $1 \times N$ weight vector $\mathbf{w}_r^\dagger$ to the received $N \times 1$ signal at the ST, the received scalar signal from the PT at the ST in the first time slot can be written as

$$y = \sqrt{\mathrm{P_{PU}}} \mathbf{w}_r^\dagger \mathbf{h}_{\mathrm{PU}} x_{\mathrm{PU}} + \mathbf{w}_r^\dagger \mathbf{n}_1 \ , \quad (2)$$

where $\mathbf{h}_{\mathrm{PU}}$ is the $N \times 1$ channel vector from the PT to the ST, $\mathbf{n}_1$ is the $N \times 1$ AWGN vector with $\mathbf{n}_1 \sim \mathcal{CN}(\mathbf{0}_N, \mathbf{I}_N \sigma^2)$ and $(\cdot)^\dagger$ denotes conjugate transpose.

In the second time slot, the ST amplifies and forwards the PT's signal in addition to transmitting its own signal. To enable the concurrent transmission of the PT's and ST's signals, the ST applies the $N \times 1$ transmit weight vectors, $\mathbf{w}_{t_{\mathrm{PU}}}$ and $\mathbf{w}_{t_{\mathrm{SU}}}$, to each of the the PT's and the ST's signals respectively in order to cancel the interference among the PT's and the ST's signals. Thus, the received scalar signal at the PR from the ST can be written as

$$\begin{aligned} r_{\mathrm{PU},2} &= Q_r \mathbf{g}_{\mathrm{PU}}^\dagger \left(\sqrt{\beta} \mathbf{w}_{t_{\mathrm{PU}}} Q_y y + \sqrt{1-\beta} \mathbf{w}_{t_{\mathrm{SU}}} x_{\mathrm{SU}} \right) + n_2 \\ &= Q_r Q_y \sqrt{P_{\mathrm{PU}}} \sqrt{\beta} \mathbf{g}_{\mathrm{PU}}^\dagger \mathbf{w}_{t_{\mathrm{PU}}} \mathbf{w}_r^\dagger \mathbf{h}_{\mathrm{PU}} x_{\mathrm{PU}} \\ &\quad + \sqrt{1-\beta} Q_r \mathbf{g}_{\mathrm{PU}}^\dagger \mathbf{w}_{t_{\mathrm{SU}}} x_{\mathrm{SU}} \\ &\quad + \sqrt{\beta} Q_r Q_y \mathbf{g}_{\mathrm{PU}}^\dagger \mathbf{w}_{t_{\mathrm{PU}}} \mathbf{w}_r^\dagger \mathbf{n}_1 + n_2 \ , \end{aligned} \quad (3)$$

where $\mathbf{g}_{\mathrm{PU}}$ is the $N \times 1$ channel vector from the ST to the PR, x_{SU} is the transmitted scalar data from the ST with $\mathrm{E}[|x_{\mathrm{SU}}|^2] = 1$, β is the power allocation number, used to allocate the available power at the ST between the PU's and the SU's signal with $0 \le \beta \le 1$, and n_2 is the AWGN at the PR with $n_2 \sim \mathcal{CN}(0, \sigma^2)$. In addition, Q_y is the normalization constant applied to normalize the PU's signal power received at the ST, and is given by

$$Q_y = \sqrt{1/\alpha_y} \ , \quad (4)$$

where

$$\alpha_y = \mathbf{w}_r^\dagger \left(P_{\mathrm{PU}} \mathbf{h}_{\mathrm{PU}} \mathbf{h}_{\mathrm{PU}}^\dagger + \sigma^2 \right) \mathbf{w}_r \ , \quad (5)$$

and Q_r is the normalization constant designed to ensure that the short term total transmit power at the ST is constrained, and is given by

$$Q_r = \sqrt{P_r/\alpha_r} \ , \quad (6)$$

where α_r is given by

$$\alpha_r = \mathrm{Trace} \left(\beta \mathbf{w}_{\mathrm{t_{PU}}} \mathbf{w}_{\mathrm{t_{PU}}}^\dagger + (1-\beta) \mathbf{w}_{\mathrm{t_{SU}}} \mathbf{w}_{\mathrm{t_{SU}}}^\dagger \right) \ . \quad (7)$$

The received scalar signal at the SR in the second time slot can be written as

$$\begin{aligned} r_{\mathrm{SU}} &= Q_r \mathbf{g}_{\mathrm{SU}}^\dagger \left(\sqrt{1-\beta} \mathbf{w}_{t_{\mathrm{SU}}} x_{\mathrm{SU}} + \sqrt{\beta} Q_y \mathbf{w}_{t_{\mathrm{PU}}} y \right) + n_3 \\ &= Q_r \sqrt{1-\beta} \mathbf{g}_{\mathrm{SU}}^\dagger \mathbf{w}_{t_{\mathrm{SU}}} x_{\mathrm{SU}} \\ &\quad + \sqrt{\beta} Q_r Q_y \sqrt{P_{\mathrm{PU}}} \mathbf{g}_{\mathrm{SU}}^\dagger \mathbf{w}_{t_{\mathrm{PU}}} \mathbf{w}_r^\dagger \mathbf{h}_{\mathrm{PU}} x_{\mathrm{PU}} \\ &\quad + Q_r Q_y \sqrt{\beta} \mathbf{g}_{\mathrm{SU}}^\dagger \mathbf{w}_{t_{\mathrm{PU}}} \mathbf{w}_r^\dagger \mathbf{n}_1 + n_3 \ , \end{aligned} \quad (8)$$

where $\mathbf{g}_{\mathrm{SU}}$ is the $N \times 1$ channel vector from the ST to the SR and n_3 is the AWGN at SR with $n_3 \sim \mathcal{CN}(0, \sigma^2)$. Throughout this paper, all channels are assumed to exhibit independent and identically distributed (i.i.d.) flat Rayleigh fading. Furthermore, we assume that the channel coefficient vectors $\mathbf{h}_{\mathrm{PU}}, \mathbf{g}_{\mathrm{PU}}$ and $\mathbf{g}_{\mathrm{SU}}$ are perfectly known at both the ST and the SR, respectively. The signals $r_{\mathrm{PU},1}, r_{\mathrm{PU},2}$ are combined at the PR using MRC. Hence, the total received signal to interference and noise ratio (SINR) at the PR can be written as

$$\gamma_{\mathrm{PU}} = \frac{P_{\mathrm{PU}} |h_d|^2}{\sigma^2} + \frac{P_{\mathrm{PU}} Q_r^2 Q_y^2 \beta |\mathbf{g}_{\mathrm{PU}}^\dagger \mathbf{w}_{t_{\mathrm{PU}}} \mathbf{w}_r^\dagger \mathbf{h}_{\mathrm{PU}}|^2}{I_{\mathrm{SU}} + \sigma^2} \ , \quad (9)$$

while the received SINR at the SR is given by

$$\gamma_{\mathrm{SU}} = \frac{Q_r^2 (1-\beta) |\mathbf{g}_{\mathrm{SU}}^\dagger \mathbf{w}_{t_{\mathrm{SU}}}|^2}{I_{\mathrm{PU}} + \sigma^2} \ , \quad (10)$$

where $I_{\mathrm{PU}} = Q_r^2 Q_y^2 \beta P_{\mathrm{PU}} |\mathbf{g}_{\mathrm{SU}}^\dagger \mathbf{w}_{t_{\mathrm{PU}}} \mathbf{w}_r^\dagger \mathbf{h}_{\mathrm{PU}}|^2 + Q_r^2 Q_y^2 \beta \sigma^2 |\mathbf{g}_{\mathrm{SU}}^\dagger \mathbf{w}_{t_{\mathrm{PU}}} \mathbf{w}_r^\dagger|^2$ and $I_{\mathrm{SU}} = Q_r^2 (1-\beta) |\mathbf{g}_{\mathrm{PU}}^\dagger \mathbf{w}_{t_{\mathrm{SU}}}|^2 + Q_r^2 Q_y^2 \beta \sigma^2 |\mathbf{g}_{\mathrm{PU}}^\dagger \mathbf{w}_{t_{\mathrm{PU}}} \mathbf{w}_r^\dagger|^2$. By using a proper weight design at the ST, our proposed two time slots transmission scheme results in an efficient spectral sharing between the PU and the SU networks. In particular, by using the ST to relay the PU signal, the PU will achieve a higher diversity gain than a conventional non-cooperative relaying scheme, which results in improving the PU's performance. Meanwhile, due to the fact that the PT will remain silent during the second time slot in our scheme, the SU network will achieve better performance compared with the non corporative case as the SR will receive the ST signal, without any interference from the PT in the second time slot.

Digital Object Identifier: 10.4108/ICST.CROWNCOM2010.9260
http://dx.doi.org/10.4108/ICST.CROWNCOM2010.9260

III. Proposed Weights Design

In this section, we will propose a practical design of the antenna weights at the ST, which allows an efficient spectral sharing between the PU and the SU network, as described in the previous section. According to our proposed transmission scheme, in the first time slot, the PT will only be transmitting while the ST will be silent. Therefore, all of the antennas at the ST can be used to receive the PT signal and the MRC technique will be optimal in this scenario. According to the principles of MRC, we choose

$$\mathbf{w}_r = \frac{\mathbf{h}_{\mathrm{PU}}}{\|\mathbf{h}_{\mathrm{PU}}\|} \; , \tag{11}$$

where $\|.\|$ is the Frobenius norm. In the second time slot, the ST amplifies and forwards the PT's signal in addition to transmitting its own signal. Thus, the transmit weights vectors, $\mathbf{w}_{t_{\mathrm{PU}}}$ and $\mathbf{w}_{t_{\mathrm{PU}}}$, should be designed such that the interference among the PT's and the ST's signals is canceled. There are several techniques that can be used to choose the design of $\mathbf{w}_{t_{\mathrm{PU}}}$ and $\mathbf{w}_{t_{\mathrm{SU}}}$ to cancel the interference among the PT's and the ST's signals at the ST. One such technique for canceling interference is the use of sophisticated multiple antenna signal processing techniques, such as zero forcing (ZF) or minimum mean square error. In this paper, we consider a ZF approach, because it is a practical and simple scheme often considered for interference cancelation, and requires significantly lower complexity than the other interference cancelation schemes. Furthermore, note that in order to apply the ZF principles at the ST, we make the common assumption that the number of antennas at the ST is $N \geq 2$.

According to the ZF principles, the transmit weight vector $\mathbf{w}_{t_{\mathrm{PU}}}$ is chosen in the orthogonal space of $\mathbf{g}_{\mathrm{SU}}^{\dagger}$ such that $|\mathbf{g}_{\mathrm{SU}}^{\dagger}\mathbf{w}_{t_{\mathrm{PU}}}| = 0$ and $|\mathbf{g}_{\mathrm{PU}}^{\dagger}\mathbf{w}_{t_{\mathrm{PU}}}|$ is maximized. Similarly, $\mathbf{w}_{t_{\mathrm{SU}}}$ is chosen in the orthogonal space of $\mathbf{g}_{\mathrm{PU}}^{\dagger}$ such that $|\mathbf{g}_{\mathrm{PU}}^{\dagger}\mathbf{w}_{t_{\mathrm{SU}}}| = 0$ and $|\mathbf{g}_{\mathrm{SU}}^{\dagger}\mathbf{w}_{t_{\mathrm{SU}}}|$ is maximized. Thus, the problem of designing the transmit weights, $\mathbf{w}_{t_{\mathrm{PU}}}$ and $\mathbf{w}_{t_{\mathrm{SU}}}$ at the ST, using ZF principles can be formulated as

$$\begin{aligned}
&1)\quad \text{maximize} \quad |\mathbf{g}_{\mathrm{PU}}^{\dagger}\mathbf{w}_{t_{\mathrm{PU}}}| \\
&\qquad \text{subject to} \quad |\mathbf{g}_{\mathrm{SU}}^{\dagger}\mathbf{w}_{t_{\mathrm{PU}}}| = 0 \quad \text{and} \quad \|\mathbf{w}_{t_{\mathrm{PU}}}\| = 1. \\
&2)\quad \text{maximize} \quad |\mathbf{g}_{\mathrm{SU}}^{\dagger}\mathbf{w}_{t_{\mathrm{SU}}}| \\
&\qquad \text{subject to} \quad |\mathbf{g}_{\mathrm{PU}}^{\dagger}\mathbf{w}_{t_{\mathrm{SU}}}| = 0 \quad \text{and} \quad \|\mathbf{w}_{t_{\mathrm{SU}}}\| = 1.
\end{aligned} \tag{12}$$

Using the projection matrix theory [7], the weights $\mathbf{w}_{t_{\mathrm{PU}}}$ and $\mathbf{w}_{t_{\mathrm{SU}}}$ which achieves (12), can be found as follows

$$\mathbf{w}_{t_{\mathrm{PU}}} = \frac{\mathbf{A}_{\mathrm{PU}}^{\perp}\mathbf{g}_{\mathrm{PU}}}{\|\mathbf{A}_{\mathrm{PU}}^{\perp}\mathbf{g}_{\mathrm{PU}}\|} \quad \text{and} \quad \mathbf{w}_{t_{\mathrm{SU}}} = \frac{\mathbf{A}_{\mathrm{SU}}^{\perp}\mathbf{g}_{\mathrm{SU}}}{\|\mathbf{A}_{\mathrm{SU}}^{\perp}\mathbf{g}_{\mathrm{SU}}\|} \; , \tag{13}$$

where $\mathbf{A}_{\mathrm{PU}}^{\perp}$ and $\mathbf{A}_{\mathrm{SU}}^{\perp}$ are the projection matrices for the PU and SU respectively given by

$$\mathbf{A}_{\mathrm{PU}}^{\perp} = (\mathbf{I} - \mathbf{g}_{\mathrm{SU}}(\mathbf{g}_{\mathrm{SU}}^{\dagger}\mathbf{g}_{\mathrm{SU}})^{-1}\mathbf{g}_{\mathrm{SU}}^{\dagger}) \tag{14}$$

and

$$\mathbf{A}_{\mathrm{SU}}^{\perp} = (\mathbf{I} - \mathbf{g}_{\mathrm{PU}}(\mathbf{g}_{\mathrm{PU}}^{\dagger}\mathbf{g}_{\mathrm{PU}})^{-1}\mathbf{g}_{\mathrm{PU}}^{\dagger}) \; . \tag{15}$$

Substituting (11) and (13) in (9), (10), (5) and (7) will result respectively in

$$\gamma_{\mathrm{PU}} = \frac{P_{\mathrm{PU}}|h_d|^2}{\sigma_{PU}^2} + \frac{Q_r^2 Q_y^2 \beta P_{\mathrm{PU}}\|\mathbf{A}_{\mathrm{PU}}^{\perp}\mathbf{g}_{\mathrm{PU}}\|^2\|\mathbf{h}_{\mathrm{PU}}\|^2}{Q_r^2 Q_y^2 \beta \sigma^2\|\mathbf{A}_{\mathrm{PU}}^{\perp}\mathbf{g}_{\mathrm{PU}}\|^2 + \sigma^2} \; , \tag{16}$$

$$\gamma_{\mathrm{SU}} = \frac{Q_r^2(1-\beta)\|\mathbf{A}_{\mathrm{SU}}^{\perp}\mathbf{g}_{\mathrm{SU}}\|^2}{\sigma^2} \; , \tag{17}$$

$$\alpha_y = P_{\mathrm{PU}}\|\mathbf{h}_{\mathrm{PU}}\|^2 + \sigma^2 \qquad \text{and} \qquad \alpha_r = 1. \tag{18}$$

Thus, the final expression for the SINR at the PR and the SR, after substituting Q_r and Q_y given in (6) and (4) respectively, can be written as

$$\begin{aligned}
\gamma_{\mathrm{PU}} &= \gamma_D + \gamma_R = \gamma_D + \frac{\gamma_1\gamma_2}{\gamma_1+\gamma_2+1} \\
&= \bar{\gamma_D}|h_d|^2 + \frac{\bar{\gamma_1}\|\mathbf{h}_{\mathrm{PU}}\|^2\bar{\gamma_2}\|\mathbf{A}_{\mathrm{PU}}^{\perp}\mathbf{g}_{\mathrm{PU}}\|^2}{\bar{\gamma_1}\|\mathbf{h}_{\mathrm{PU}}\|^2 + \bar{\gamma_2}\|\mathbf{A}_{\mathrm{PU}}^{\perp}\mathbf{g}_{\mathrm{PU}}\|^2 + 1}
\end{aligned} \tag{19}$$

and

$$\gamma_{\mathrm{SU}} = \bar{\gamma_{\mathrm{SU}}}\|\mathbf{A}_{\mathrm{SU}}^{\perp}\mathbf{g}_{\mathrm{SU}}\|^2 \; , \tag{20}$$

where $\bar{\gamma_D} = \frac{P_{\mathrm{PU}}}{\sigma^2}, \bar{\gamma_1} = \frac{P_{\mathrm{PU}}}{\sigma^2}\ \bar{\gamma_2} = \frac{P_r\beta}{\sigma^2}$ and $\bar{\gamma_{\mathrm{SU}}} = \frac{P_r(1-\beta)}{\sigma^2}$.

Note that we can incorporate different positions of the PT, PR, ST and SR, by appropriately scaling the average transmit SNR at the PT and the ST in (19) and (20) respectively, as follows

$$\begin{aligned}
\bar{\gamma_D} &= \frac{P_{\mathrm{PU}}}{d_{\mathrm{PT,PR}}^{\nu}\sigma^2}, \quad \bar{\gamma_1} = \frac{P_{\mathrm{PU}}}{d_{\mathrm{PT,ST}}^{\nu}\sigma^2}, \\
\bar{\gamma_2} &= \frac{P_r\beta}{d_{\mathrm{ST,PR}}^{\nu}\sigma^2} \quad \text{and} \quad \bar{\gamma_{\mathrm{SU}}} = \frac{P_r(1-\beta)}{d_{\mathrm{ST,SR}}^{\nu}\sigma^2}
\end{aligned} \tag{21}$$

where ν is the path loss exponent, $d_{\mathrm{PT,ST}}$ is the distance between the PT and the ST, $d_{\mathrm{ST,PR}}$ is the distance between the ST and the PR, $d_{\mathrm{PT,PR}}$ is the distance between the PT and the PR and $d_{\mathrm{ST,SR}}$ is the distance between the ST and the SR.

IV. Analysis and Results

In this section, we analyze the performance of the proposed two time slots transmission scheme, by using the designed weights in (11) and (13). In order to analyze the performance of the proposed scheme, we consider the BER and the ergodic capacity achieved at each of the PR and the SR as performance measures. For ease of presentation, we considered a system topology where PT, PR, ST, and SR are collinear. In a two-dimensional X-Y plane, PT and PR are located at points (0, 0) and (2, 0) respectively, thus $d_{\mathrm{PT,PR}} = 2$ whereas ST moves on the positive X axis. In all of our simulations, we have chosen $d_{\mathrm{PT,ST}} = 1, d_{\mathrm{ST,PR}} = |2 - d_{\mathrm{PT,ST}}| = 1$ and $d_{\mathrm{ST,SR}} = 1$. In addition, the SNR is defined as, $\mathrm{SNR} = \frac{P_{\mathrm{pu}}}{\sigma^2} = \frac{P_r}{\sigma^2}$ and the path loss exponent remains at $\nu = 4$ in all simulations.

Digital Object Identifier: 10.4108/ICST.CROWNCOM2010.9260
http://dx.doi.org/10.4108/ICST.CROWNCOM2010.9260

A. Error Performance

In this section, we first analyze the performance of the proposed two time slots transmission scheme by deriving the diversity gain achieved at each of the PU and the SU. Then, we present the simulation results for the bit error rate (BER) achieved at each of the PU and the SU to evaluate the performance of the proposed scheme.

1) Evaluation of The Diversity Gain : The diversity gain is one of the key factors governing system performance in the high SNR regime. We now present a closed form expression for the diversity gain achieved at each of the PU and the SU, given by the following theorem.

Theorem 1: At high SNR, the diversity gain achieved at each of the PU and the SU, using the weights in (11) and (13), is respectively given by

$$G_{d_{\rm PU}} = N \quad \text{and} \quad G_{d_{\rm SU}} = N - 1 \tag{22}$$

Proof: Since the received SINR at the PR $\gamma_{\rm PU}$ in (19) has the form of $\gamma_{\rm PU} = \gamma_D + \gamma_R$, we can use results in [8, Proposition 4], from which we can express the aggregate diversity gain $G_{d_{\rm PU}}$ achieved at the PR as

$$G_{d_{\rm PU}} = G_{d_D} + G_{d_R} \tag{23}$$

where G_{d_D} and G_{d_R} are the diversity gain of γ_D and γ_R respectively. Note that γ_D in (19) is distributed as exponential random variable (RV). Thus, the diversity order of γ_D is given by [8]

$$G_{d_D} = 1 \tag{24}$$

Note that γ_R in (19) has the form of $\gamma_R = \frac{\gamma_1 \gamma_2}{\gamma_1 + \gamma_2 + 1}$ where γ_1 and γ_2 are given in (19). Note that γ_1 is distributed as chi-squared RV with $2N$ degrees of freedom. Using Theorem 4.21 and Theorem 4.22 in [7] and [9, Theorem 5.5.1], it can be shown that γ_2 and the received SINR at the SU $\gamma_{\rm SU}$ in (20) are distributed as chi-squared RV with $2(N-1)$ degrees of freedom. Based on this, the diversity gain achieved at the SU is given by $G_{d_{\rm SU}} = N - 1$. Note that the diversity gain of γ_R, with γ_1 and γ_2 being distributed as as chi-squared RV, has been derived in [10]. Using the results in [10], it can be shown that that the diversity gain of γ_R is given by

$$G_{d_R} = N - 1 \tag{25}$$

by substituting (24) and (25) in (23) we obtain the desired result. ∎

2) Simulation Results: Fig. 2 shows the simulation results of the BER at the PU and the SU using our proposed two time slots transmission scheme, and the BER at the PU achieved by continuous transmission through the direct link only using one time slot, when the numbers of antennas at the ST $N = 2$ and 4. For a fair comparison between the two schemes, we used the 16-QAM modulation scheme for the two time slots transmission scheme and QPSK modulation scheme for the one time slot transmission scheme, in order to maintain the same spectral efficiency.

It is clear that the PU's BER performance using our proposed scheme, using two time slots, outperforms the PU's BER performance, achieved using the direct transmission scheme using one time slot, for all values of the SNR and for all values of N, which is a definite advantage of our scheme. Furthermore, it is clear the PU's BER performance, using the two time slots transmission scheme, improves substantially and is superior to the PU's BER performance, achieved using one time slot transmission scheme, as N increases. This can be explained by the fact that increasing N will result in increasing the diversity gain achieved at the PR in (22).

Another advantage of our scheme is that the SU, using our proposed two time slots transmission scheme, achieves a good BER performance as shown in Fig. 2. In particular, the SU's BER performance, using the two time slots transmission scheme, improves substantially and approaches the PU's BER performance, using the two time slots transmission scheme, as the number of antennas N at the ST increases, and outperforms the PU's BER performance achieved, with one time slot transmission scheme through the direct link, for all values of N. This can be explained by the fact that increasing N will result in increasing the diversity gain achieved at the SR in (22).

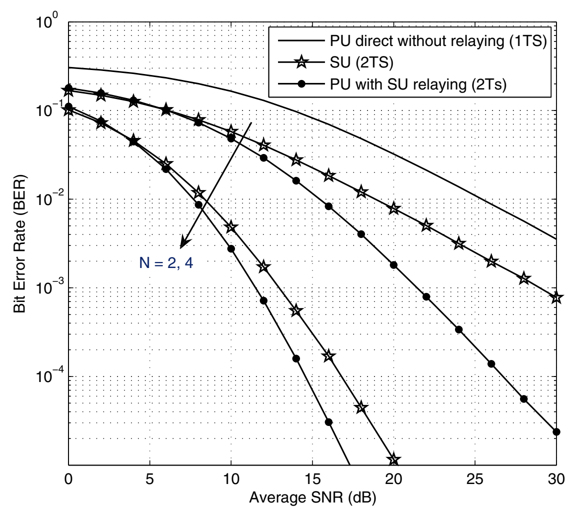

Fig. 2. BER for $N = 2$ and 4 with $\beta = 0.5$.

B. Ergodic Capacity

We now present the simulation results for the ergodic capacity achieved at the PU and the SU, using our proposed two time slots transmission scheme, as well as the ergodic capacity at the PU, using the one time slot transmission scheme through the direct link only. For a fair comparison between the two schemes in our simulations, the ergodic capacity achieved at the PU and SU, using the two time slots transmission scheme,

Digital Object Identifier: 10.4108/ICST.CROWNCOM2010.9260
http://dx.doi.org/10.4108/ICST.CROWNCOM2010.9260

is calculated respectively as follows

$$R_{\mathrm{PU}} = \frac{1}{2}\mathbf{E}\left[\log_2\left(1+\gamma_{\mathrm{PU}}\right)\right] \quad (26)$$

and

$$R_{\mathrm{SU}} = \frac{1}{2}\mathbf{E}\left[\log_2\left(1+\gamma_{\mathrm{SU}}\right)\right] \ , \quad (27)$$

while the ergodic capacity achieved at the PU, using the one time slot transmission scheme, is estimated as follows

$$R_{\mathrm{PU,D}} = \mathbf{E}\left[\log_2\left(1+\gamma_{\mathrm{D}}\right)\right] \quad (28)$$

where $\gamma_{\mathrm{PU}}, \gamma_{\mathrm{D}}$ and γ_{SU} are given in (19) and (20) respectively. Note that R_{SU} and R_{PU} are multiplied by factor of $\frac{1}{2}$ to consider the loss in the capacity because of using two time slots to transmit each of the PU and SU signal.

Fig. 3 show the simulation results of the ergodic capacity achieved at the PU and the SU, using our proposed two time slots transmission scheme, as well as the ergodic capacity at the PU, with the one time slot transmission scheme through the direct link only, when the number of antennas at the ST $N = 2$ and 4 respectively. It is clear that PU's ergodic capacity, of our two time slots transmission scheme, outperforms the PU's ergodic capacity, achieved by using the one time slot transmission scheme, for a practical range of the SNR values and for a practical numbers of antennas, which shows the superiority of our scheme. Moreover, it is clear that the PU's ergodic capacity, with the two time slots transmission scheme, improves substantially and is more superior to the PU's ergodic capacity, achieved using one time slot transmission scheme, as N increases. This can be explained by the fact that that increasing N will result in increasing the diversity gain achieved at the PR in (22).

Another advantage of our scheme is that the SU, with the proposed two time slots transmission scheme, achieves a good ergodic capacity as it can be seen from Fig. 3. In particular, the SU's ergodic capacity, with the two time slots transmission, improves substantially and approaches the PU's ergodic capacity, achieved with the two time slots, as the number of antennas N at the ST increases.

V. Conclusions

In this paper, we have proposed and investigated a solution for spectrum leasing based on the idea that SU can earn spectrum access in exchange for cooperation with the PU. We have proposed the design of a spectrum sharing scheme which will result in higher data rate and improved error performance for the PU and SU networks over practical SNR values and numbers of antennas, compared to conventional systems where no cooperation occurs. We have provided analytical and numerical results that have confirmed the considered model as a promising paradigm for CR networks. Future works may include comparing the sum rate and sum BER of the PU and SU networks using our proposed scheme and the conventional direct transmission scheme.

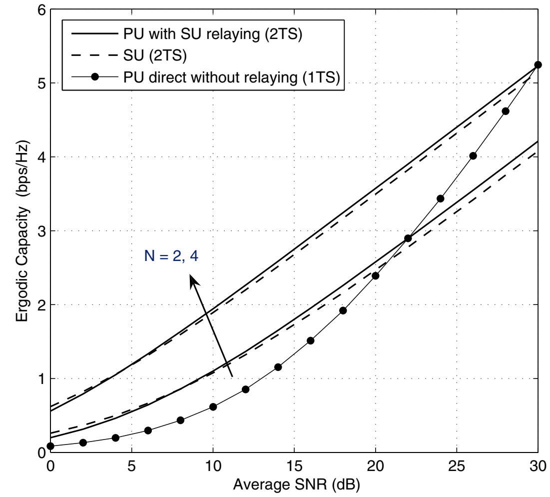

Fig. 3. Ergodic capacity for $N = 2$ and 4 with $\beta = 0.5$.

Acknowledgment

This work was partially supported by the research grant DP0773173 awarded by the Australian Research Council and Norman I Price scholarship. The authors would like to acknowledge the valuable discussions with Dr. Wibowo Hardjawana from The University of Sydney, Australia.

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Digital Object Identifier: 10.4108/ICST.CROWNCOM2010.9260
http://dx.doi.org/10.4108/ICST.CROWNCOM2010.9260