Cooperative Decode-and-Forward Relaying for Secondary Spectrum Access

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***Abstract*—We propose a two-phase protocol based on cooperative decode-and-forward relaying for a secondary system to achieve spectrum access along with a primary system. The primary and secondary systems comprise of a transmitter-receiver pair, PT-PR and ST-SR, respectively. In the first transmission phase, PT transmits the primary signal to PR, which is also received by ST and SR, where it is decoded. At ST, the primary signal is regenerated and linearly combined with the secondary signal by assigning fractions α and $(1-\alpha)$ of the available power to the primary and secondary signals respectively. This combined signal is then broadcasted by ST in the second transmission phase. We show that as long as ST is located within a critical radius from PT, there exists a threshold value for α above which the outage probability of the primary system will be equal to or lower than the case without spectrum sharing. We also determine the outage probability achieved by the secondary system. Theoretical and simulation results confirm the efficiency of the proposed spectrum sharing scheme.**

***Index Terms*—Spectrum sharing, cooperative transmission, decode-and-forward relaying, cognitive radios.**

I. INTRODUCTION

MODERN radio spectrum management is faced with the challenge of accommodating a growing number of wireless applications and services on a limited amount of spectrum. While spectrum allocation charts [1] show that most of the spectrum is already allocated under license, spectrum measurements indicate that large amounts of such licensed spectrum is in fact under-utilized [2]. Interest has thus grown in alternate models for sharing spectrum among wireless systems [3]–[6].

Cognitive radios [5], [6] are considered in the framework of hierarchical spectrum sharing where two different wireless systems are allowed to operate over the same portion of spectrum albeit with different priorities. The system with higher priority is termed as the primary system and the one with lower priority is termed as the secondary system. The higher priority for primary system is guaranteed by the constraint that the secondary system accesses spectrum without adversely affecting the primary system. One way to achieve this constraint is by determining vacant portions of the licensed spectrum and limiting secondary transmissions to such portions [4], [6].

A number of alternate spectrum sharing models for secondary spectrum access have emerged in literature [7]–[12] as spectrum regulatory policies evolve [13], [14]. In particular, [7]–[10], [15] have studied different forms of cooperation in cognitive radios. The role of cooperative transmission, albeit in a non-causal fashion, in cognitive radios has been treated in [9]. Cooperative relaying for spectrum sensing in multi-user cognitive radios has been considered in [15]. A network model similar to ours has also been considered recently in [10]. However, in [10], the primary system *fully* controls the spectrum sharing mechanism based on cooperative transmission. Specifically, the primary system obtains instantaneous/statistical channel state information of both primary and secondary systems, and the primary transmitter decides whether to lease a certain portion of its own transmission time to the secondary system. In return, the secondary system has to spare a fraction of the leased time to help relay the primary transmission.

In this paper, we propose a spectrum sharing protocol based on controlled cooperative relay transmission. The primary system, comprising of a primary transmitter (PT) and primary receiver (PR), has licensed rights to operate in a certain portion of the spectrum and it supports the relaying functionality [16]. The secondary system, comprising of a secondary transmitter (ST) and secondary receiver (SR), can only operate on a secondary basis in this spectrum, with the constraint that its operation does not affect the primary system performance. Furthermore, we assume that the secondary system is able to follow the same radio protocols (e.g., channel coding, synchronization, etc.) as the primary system. We quantify the primary system priority in terms of its outage probability. Note that in [11], [12], an alternate metric of priority namely average rate was used.

The secondary system insures the primary system performance by adopting the following transmission protocol. In the first transmission phase, the primary signal transmitted by PT to PR is also received and decoded by ST and SR[1]. The primary signal is then regenerated at ST and superimposed with the secondary signal. A fraction, α where $0 \leq \alpha \leq 1$, of the total power at ST is allocated to the primary signal, with the remaining power assigned to the secondary signal. This weighted linear composite signal is then broadcasted by ST in the second transmission phase. At PR, a maximum

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[1] If ST fails to decode, it will remain silent in the second transmission phase, and PR will try to decode by using only the signal it received in the first transmission phase. An outage will be declared for the secondary system if either ST or SR (or both) fails to decode the primary signal. The details of the proposed protocol will be explained in the next section.

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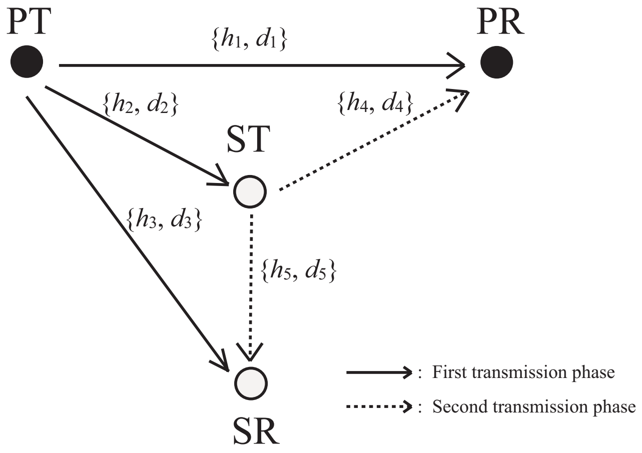

Fig. 1. System configuration.

ratio combination (MRC) of the received signals in the two transmission phases is applied to retrieve the primary signal. At SR, interference cancelation is first applied to cancel the primary signal component and then the secondary signal is retrieved. Note that the choice of $\alpha = 1$ in our proposed protocol reduces to the case of cooperative relaying with the decode-and-forward protocol as considered in [16].

In the proposed spectrum sharing protocol, the primary system only has to be aware of a "decode-and-forward relaying mode" operation. This switch to a relaying mode can be easily conveyed to the primary system through the use of control messages. The primary system does not have to be cognizant of whether the relaying node is a node belonging to the primary system or the secondary system, nor does it need to know the choice of α. From the perspective of the primary system, ST acts as a decode-and-forward relay and appears to be part of a conventional cooperative communication system [16].

We analytically derive the outage probabilities of the primary and secondary systems under the proposed protocol. We show that as long as ST is located within a critical radius from PT, there exists a threshold value for α, above which the secondary system can operate without affecting the outage performance of the primary system. By controlling α, the outage probability of the primary system can either be maintained to be the same as the case without spectrum sharing, or it can be improved by a desired margin.

Notations: A circularly symmetric complex Gaussian random variable z with variance σ^2 is denoted as $z \sim \mathcal{CN}(0, \sigma^2)$. An exponential distributed random variable x with mean $\frac{1}{\lambda}$ is denoted as $x \sim \mathcal{E}(\lambda)$. An identity matrix of size m is denoted as $\boldsymbol{I}_m$. We use $E\{\cdot\}$ to denote expectation. We also denote the transpose and conjugate transpose of matrix $\boldsymbol{A}$ as $\boldsymbol{A}^{\mathrm{T}}$ and $\boldsymbol{A}^{\mathrm{H}}$, respectively.

II. PROTOCOL DESCRIPTION AND PERFORMANCE ANALYSIS

The system configuration of the proposed scheme is shown in Fig. 1. The channels over links PT→PR, PT→ST, PT→SR, ST→PR, and ST→SR are modeled to be Rayleigh flat fading with channel coefficients denoted by h_1, h_2, h_3, h_4, and h_5 respectively. We have $h_i \sim \mathcal{CN}(0, d_i^{-\nu})$, $i = 1, 2, 3, 4, 5$, where ν is the path loss exponent and d_i is the normalized distance between the respective transmitters and receivers. This normalization is done with respect to the distance between PT and PR, i.e. $d_1 = 1$. Thus each of the links can be characterized by the set of parameters $\{h_i, d_i\}$ as shown in Fig. 1, and we also denote $\gamma_i = |h_i|^2$. Let x_p and x_s denote the primary and secondary signals respectively, with zero mean and $E\{x_p^* x_p\} = 1$, $E\{x_s^* x_s\} = 1$. The transmit power at PT and ST is denoted as P_p and P_s respectively.

A. Outage performance of primary system

We consider a two-phase transmission protocol. In the first transmission phase, as shown by the solid lines in Fig. 1, the primary signal x_p is transmitted by PT. Denoting the signals received by PR, ST, and SR in the first transmission phase as y_{11}, y_{21}, and y_{31} respectively, we have

$$y_{j1} = \sqrt{P_p} h_j x_p + n_{j1} \tag{1}$$

where $j = 1, 2, 3$. Here, $n_{j1} \sim \mathcal{CN}(0, \sigma^2)$ is the additive white Gaussian noise (AWGN) in the respective receivers for the first transmission phase. The achievable rate between PT and ST is thus given by $R_2 = \frac{1}{2}\log_2\left(1 + \frac{P_p\gamma_2}{\sigma^2}\right)$, where the factor of $\frac{1}{2}$ accounts for the fact that the overall transmission is being split into two phases. After reception in the first transmission phase, ST attempts to decode x_p. If the decoding is successful, ST regenerates x_p. A composite signal z_s is generated by linearly combining the regenerated signal x_p with power αP_s and the secondary signal x_s with power $(1-\alpha)P_s$, where α $(0 \leq \alpha \leq 1)$ is the power allocation factor. Thus $z_s = \sqrt{\alpha P_s} x_p + \sqrt{(1-\alpha)P_s} x_s$.

In the second transmission phase, as depicted by the dotted lines in Fig. 1, z_s is broadcasted and received by PR and SR. The signal received at PR is given by $y_{12} = h_4 z_s + n_{12} = \left(\sqrt{\alpha P_s} h_4\right) x_p + \left(\sqrt{(1-\alpha)P_s} h_4\right) x_s + n_{12}$, where $n_{12} \sim \mathcal{CN}(0, \sigma^2)$ is the AWGN at PR in the second transmission phase. Signals y_{11} and y_{12} are then combined at PR using MRC for the decoding of x_p. Note that the two-phase transmission of x_p can be written as an equivalent single-input-multiple-output (SIMO) channel, i.e. $\boldsymbol{y} = \boldsymbol{h} x_p + \boldsymbol{n}$, where $\boldsymbol{y} = [y_{11},\ y_{12}]^{\mathrm{T}}$, $\boldsymbol{h} = \left[\sqrt{P_p} h_1,\ \sqrt{\alpha P_s} h_4\right]^{\mathrm{T}}$ and $\boldsymbol{n} = \left[n_{11},\ \sqrt{(1-\alpha)P_s} h_4 x_s + n_{12}\right]^{\mathrm{T}}$. After normalizing the noise variances, we obtain

$$\tilde{\boldsymbol{y}} = \left[\frac{y_{11}}{\sqrt{\sigma^2}}, \frac{y_{12}}{\sqrt{\lambda}}\right]^{\mathrm{T}} = \tilde{\boldsymbol{h}} x_p + \tilde{\boldsymbol{n}} \tag{2}$$

where $\tilde{\boldsymbol{h}} = \left[\frac{\sqrt{P_p} h_1}{\sqrt{\sigma^2}},\ \frac{\sqrt{P_s \alpha} h_4}{\sqrt{\lambda}}\right]^{\mathrm{T}}$, $\lambda = P_s(1-\alpha)\gamma_4 + \sigma^2$, and $E\{\tilde{\boldsymbol{n}}\tilde{\boldsymbol{n}}^{\mathrm{H}} | \boldsymbol{h}\} = \boldsymbol{I}_2$. The channel vector $\boldsymbol{h}$ can be estimated at PR by using standard preamble-aided channel estimation techniques[2], thus y_{11} and y_{12} are combined by MRC, and the achievable rate between PT and PR, conditioned on the

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[2] Note that PR does not need to have explicit knowledge of α as only the products $\sqrt{P_p} h_1$ and $\sqrt{\alpha P_s} h_4$ (the elements of $\boldsymbol{h}$) are required for MRC.

successful decoding at ST, is given by

$$\begin{aligned} R_1^{\mathrm{MRC}} &= \frac{1}{2}\log_2\left(\det\left(\boldsymbol{I}_2+\tilde{\boldsymbol{h}}\tilde{\boldsymbol{h}}^{\mathrm{H}}\right)\right) \\ &= \frac{1}{2}\log_2\left(1+\frac{P_p\gamma_1}{\sigma^2}+\frac{P_s\alpha\gamma_4}{P_s(1-\alpha)\gamma_4+\sigma^2}\right). \end{aligned} \tag{3}$$

On the other hand, when ST fails to decode in the first transmission phase, it will remain silent in the second transmission phase. In this case, it is still possible for PR to decode for x_p through the direct link from PT to PR, and the achievable rate between PT and PR is given by $R_1 = \log_2\left(1+\frac{P_p\gamma_1}{\sigma^2}\right)$. The outage probability of the primary signal transmission with target rate R_{pt} is thus given as

$$\begin{aligned} P_{\mathrm{out}}^{p} &= \Pr\{R_2 > R_{pt}\}\Pr\left\{R_1^{\mathrm{MRC}} < R_{pt}\right\} \\ &\quad +\Pr\{R_2 < R_{pt}\}\Pr\left\{\frac{1}{2}R_1 < R_{pt}\right\} \\ &= 1-\Pr\{R_2 > R_{pt}\}\Pr\{R_1^{\mathrm{MRC}} > R_{pt}\} \\ &\quad -\Pr\{R_2 < R_{pt}\}\Pr\left\{\frac{1}{2}R_1 > R_{pt}\right\} \end{aligned} \tag{4}$$

where the factor of $\frac{1}{2}$ in the second term above accounts for the fact that the overall transmission is being split into two phases. Since $\gamma_1 \sim \mathcal{E}(1)$ and $\gamma_2 \sim \mathcal{E}(d_2^{\nu})$, we have

$$\Pr\left\{\frac{1}{2}R_1 > R_{pt}\right\} = \Pr\left\{\gamma_1 > \frac{\sigma^2}{P_p}\rho_1\right\} = \exp\left(-\frac{\sigma^2}{P_p}\rho_1\right), \tag{5}$$

$$\Pr\{R_2 > R_{pt}\} = \Pr\left\{\gamma_2 > \frac{\sigma^2}{P_p}\rho_1\right\} = \exp\left(-d_2^{\nu}\frac{\sigma^2}{P_p}\rho_1\right), \tag{6}$$

where $\rho_1 = 2^{2R_{pt}}-1$. Assuming $P_s \gg \sigma^2$, we obtain

$$\begin{aligned} &\Pr\{R_1^{\mathrm{MRC}} > R_{pt}\} \\ &\approx \Pr\left\{\frac{1}{2}\log_2\left(1+\frac{P_p\gamma_1}{\sigma^2}+\frac{\alpha}{1-\alpha}\right) > R_{pt}\right\} \\ &= \begin{cases} \exp\left(-\frac{\sigma^2}{P_p}\left(\rho_1-\frac{\alpha}{1-\alpha}\right)\right) & 0 \le \alpha < \widehat{\alpha} \\ 1 & \widehat{\alpha} \le \alpha \le 1 \end{cases} \end{aligned} \tag{7}$$

where $\widehat{\alpha} = \frac{\rho_1}{\rho_1+1}$. Substituting (5), (6) and (7) into (4), we have

$$P_{\mathrm{out}}^{p} \approx \begin{cases} P_{\mathrm{out}}^{p,1} & 0 \le \alpha < \widehat{\alpha} \\ P_{\mathrm{out}}^{p,2} & \widehat{\alpha} \le \alpha \le 1 \end{cases} \tag{8}$$

where $P_{\mathrm{out}}^{p,1} = 1-\exp\left(-\frac{\sigma^2}{P_p}\left((d_2^{\nu}+1)\rho_1-\frac{\alpha}{1-\alpha}\right)\right) - \exp\left(-\frac{\sigma^2}{P_p}\rho_1\right) + \exp\left(-\frac{\sigma^2}{P_p}\rho_1(d_2^{\nu}+1)\right)$ and $P_{\mathrm{out}}^{p,2} = 1-\exp\left(-d_2^{\nu}\frac{\sigma^2}{P_p}\rho_1\right)-\exp\left(-\frac{\sigma^2}{P_p}\rho_1\right)+\exp\left(-\frac{\sigma^2}{P_p}\rho_1(d_2^{\nu}+1)\right)$.

B. Critical radius from primary transmitter

Consider the scenario where the secondary system does not exist. In this case, x_p is transmitted through the direct link from PT to PR. The outage probability of the primary system with target rate R_{pt} in the absence of secondary access is thus given as

$$P_{\mathrm{out}}^{n} = \Pr\{R_1 < R_{pt}\} = 1-\exp\left(-\frac{\sigma^2}{P_p}\rho_2\right) \tag{9}$$

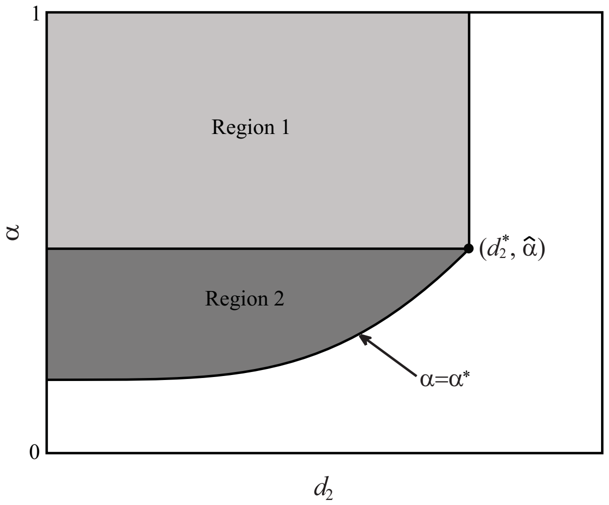

Fig. 2. Diagram of critical region for proposed scheme.

where $\rho_2 = 2^{R_{pt}}-1$.

We want to ensure that the outage probability of the primary system under the proposed scheme is equal to or smaller than the outage probability without spectrum sharing, i.e.

$$P_{\mathrm{out}}^{p} \le P_{\mathrm{out}}^{n}. \tag{10}$$

From (8), we consider the spectrum sharing requirement in (10) for the following two cases.

Case 1: $\widehat{\alpha} \le \alpha \le 1$.

Substituting $P_{\mathrm{out}}^{p,2}$ and (9) into (10), we obtain

$$d_2 \le d_2^* = \left[\frac{P_p}{\rho_1\sigma^2}\ln\left(\frac{\Phi_1-1}{\Phi_1-\Phi_2}\right)\right]^{\frac{1}{\nu}} \tag{11}$$

where $\Phi_1 = \exp\left(-\frac{\sigma^2}{P_p}\rho_1\right)$ and $\Phi_2 = \exp\left(-\frac{\sigma^2}{P_p}\rho_2\right)$. Thus, as long as $d_2 \le d_2^*$ and $\widehat{\alpha} \le \alpha \le 1$, we can achieve secondary access while satisfying (10). We draw the region that satisfies these two inequalities in a d_2-α plane and denote it as Region 1 in Fig. 2.

Case 2: $0 \le \alpha < \widehat{\alpha}$.

Substituting $P_{\mathrm{out}}^{p,1}$ and (9) into (10), we obtain

$$\alpha \ge \alpha^* = \frac{P_p\ln\left(1+\frac{\Phi_2-\Phi_1}{\Phi_3}\right)}{P_p\ln\left(1+\frac{\Phi_2-\Phi_1}{\Phi_3}\right)+\sigma^2}. \tag{12}$$

where $\Phi_3 = \exp\left(-\frac{\sigma^2}{P_p}(d_2^{\nu}+1)\rho_1\right)$. Note that α^* is monotonously increasing with respect to d_2 and it is easy to show that $\alpha^* \le \widehat{\alpha}$ (equality holds when $d_2 = d_2^*$) when $d_2 \le d_2^*$. Thus, as long as $d_2 < d_2^*$ and $\alpha^* \le \alpha < \widehat{\alpha}$, (10) is satisfied. The region that satisfies these two inequalities is drawn in Fig. 2 and is denoted as Region 2.

Combining Case 1 and Case 2, under the assumption of $P_s \gg \sigma^2$, we obtain the "critical region" of the proposed scheme, which is the union of Region 1 and Region 2 in Fig. 2. The interpretation of this critical region is that there exists a critical radius d_2^* from PT such that as long as ST is located within this radius, i.e. $d_2 \le d_2^*$, we can always find a suitable power allocation factor α between α^* and 1 to ensure that (10) is satisfied.

C. Outage performance of secondary system

We now consider the processing at SR and obtain the outage probability of the secondary system. In the first transmission phase, the signal received at SR is given as $y_{31} = \sqrt{P_p} h_3 x_p + n_{31}$. The achievable rate between PT and SR is thus given as $R_3 = \frac{1}{2}\log_2\left(1+\frac{P_p\gamma_3}{\sigma^2}\right)$. After the reception of y_{31}, SR attempts to decode x_p, and stores the decoding result if it succeeds.

In the second transmission phase, the signal received at SR is

$$\begin{aligned} y_{32} &= h_5 y_{22} + n_{32} \\ &= \left(\sqrt{\alpha P_s} h_5\right) x_p + \left(\sqrt{(1-\alpha)P_s} h_5\right) x_s + n_{32}. \end{aligned} \quad (13)$$

Here, $n_{32} \sim \mathcal{CN}(0,\sigma^2)$ is the AWGN at SR in the second transmission phase. Assuming the decoding of x_p at SR in the first transmission phase is successful, the interference component $\sqrt{\alpha P_s} h_5 x_p$ can be canceled out from (13) to obtain $y'_{32} = \left(\sqrt{(1-\alpha)P_s} h_5\right) x_s + n_{32}$. The achievable rate between ST and SR, conditioned on successful decoding of x_p at both ST and SR in the first transmission phase, is given as $R_5 = \frac{1}{2}\log_2\left(1+\frac{P_s(1-\alpha)\gamma_5}{\sigma^2}\right)$.

Note that if ST or SR (or both) is not able to decode x_p, an outage is declared for the secondary system. Thus the outage probability of the secondary system transmission with target rates R_{pt} and R_{st} for primary and secondary systems respectively, is given by

$$\begin{aligned} P_{\text{out}}^{s} &= 1 - \Pr\{R_2 > R_{pt}\}\Pr\{R_3 > R_{pt}\}\Pr\{R_5 > R_{st}\} \\ &= 1 - \exp\left(-\left(\frac{\sigma^2(d_2^\nu + d_3^\nu)\rho_1}{P_p} + \frac{\sigma^2 d_5^\nu \rho_3}{P_s(1-\alpha)}\right)\right) \end{aligned} \quad (14)$$

where $\rho_3 = 2^{2R_{st}} - 1$.

D. Remarks

We can observe from $P_{\text{out}}^{p,1}$ in (8) that with increasing α for $\alpha < \widehat{\alpha}$, more power at ST is allocated for relaying the primary signal and thus P_{out}^{p} decreases. However when $\alpha \geq \widehat{\alpha}$, P_{out}^{p} becomes independent of α and attains a constant minimum value. On the other hand, as can be observed from (14), with increasing α, less power at ST is used for x_s which causes an increase in P_{out}^{s}. This means that increasing α beyond $\widehat{\alpha}$ is counterproductive as it will only serve to increase P_{out}^{s} without any corresponding improvement in P_{out}^{p}. Thus, we should choose a power allocation factor in the range $\alpha^* \leq \alpha < \widehat{\alpha}$ to achieve an efficient outage performance tradeoff between primary and secondary systems while ensuring that (10) is satisfied. Supposing our goal is to minimize the outage probability of the primary system, it is obvious that the optimal power allocation factor is $\alpha = \widehat{\alpha}$.

Furthermore, it is worth noting that d_2^*, α^*, and $\widehat{\alpha}$ are independent of instantaneous channel realizations and can be easily obtained by ST. For instance, R_{pt} can be known by overhearing the communications between PT and PR during link setup and d_2 by channel estimation[3]. This simplicity is especially attractive for practical implementation.

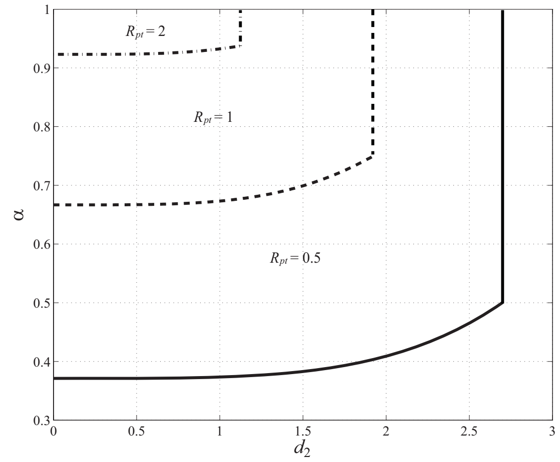

Fig. 3. Critical regions for the proposed scheme for various values of R_{pt}.

III. SIMULATION RESULTS AND DISCUSSIONS

We show the critical regions of the proposed scheme defined by (11) and (12) in a d_2-α plane for different R_{pt} in Fig. 3 with a path loss exponent $\nu = 4$. It can be observed from Fig. 3 that with decreased R_{pt}, the critical region becomes larger, which indicates that when the primary system has a lower performance requirement, secondary systems which are farther away from the primary transmitter are able to benefit from the proposed spectrum sharing scheme and the cooperating secondary system can allocate more power for its own transmission without deteriorating the primary system performance.

We consider the outage probabilities of the primary and secondary systems under different settings. We choose target rates $R_{pt} = R_{st} = 1$. The path loss exponent remains at $\nu = 4$, and $\frac{P_p}{\sigma^2} = \frac{P_s}{\sigma^2} = 20$ dB. 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 $(1,0)$ respectively, thus $d_1 = 1$. ST moves on the positive X axis, whereas SR is located in the middle of PT and ST. Therefore, $d_4 = |1 - d_2|$ and $d_3 = d_5 = \frac{1}{2}d_2$. In Fig. 4, we show both the theoretical and simulation results of the outage probabilities for $d_2 = 0.5$, $d_2 = 1.2$, and $d_2 = d_2^* = 1.92$, as the power allocation factor α is varied.

From Fig. 4 we can observe that the theoretical results agree excellently with the simulation results. When $\alpha < \widehat{\alpha} = 0.75$, the outage probability P_{out}^{p} decreases with increasing α, which is intuitively satisfying because more power is allocated at ST for the relaying of primary signal and less power is used for the transmission of secondary signal (which constitutes interference to the primary system). However, an outage

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[3] By measuring the average channel gain $\bar{\gamma}_2$ of PT-ST link, and overhearing the primary control signal regarding the average channel gain $\bar{\gamma}_1$ of PT-PR link, d_2 can be simply obtained by $d_2 = \left(\frac{\bar{\gamma}_1}{\bar{\gamma}_2}\right)^{\frac{1}{\nu}}$. We presume that, like most modern wireless systems, the primary system utilizes a feedback link for channel state information.

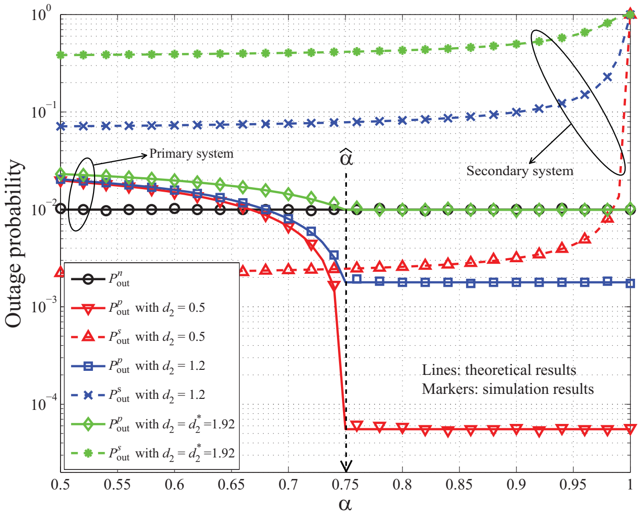

Fig. 4. Outage probability comparison for $d_2 = 0.5$, $d_2 = 1.2$, and $d_2 = d_2^* = 1.92$.

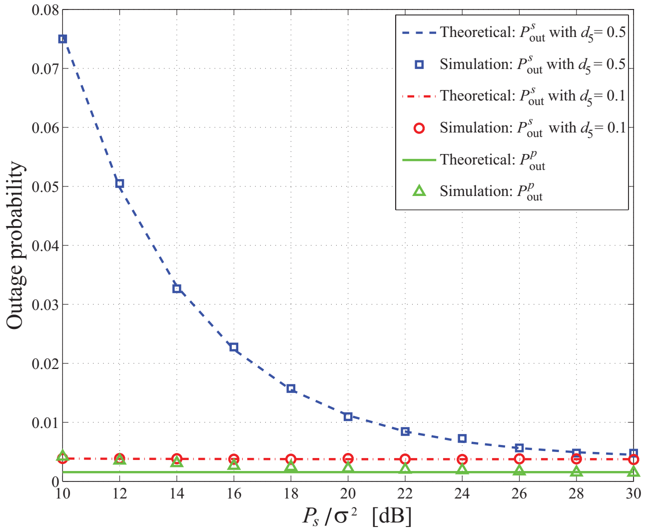

Fig. 5. Outage probability for various values of P_s/σ^2.

probability floor for P_{out}^p appears when $\alpha > \widehat{\alpha}$. This is because when α approaches unity, $\Pr\{R_1^{\text{MRC}} < R_{pt}\}$ becomes small, and the successful decoding at ST and PR (when ST fails to decode) becomes the limiting factor for primary system, i.e. $P_{\text{out}}^p \rightarrow \Pr\{R_2 < R_{pt}\}\Pr\{\frac{1}{2}R_1 < R_{pt}\}$. Thus increasing α further cannot reduce the outage probability of the primary system. This fact can also be analytically deduced from (8) as discussed in Section II-D. Furthermore, since $\Pr\{R_2 < R_{pt}\}$ becomes larger with increasing d_2, the outage probability floor for P_{out}^p becomes higher with increasing d_2. Finally, when $d_2 = d_2^*$, the outage probability floor coincides with P_{out}^n which indicates that with $d_2 > d_2^*$, the proposed scheme is not able to satisfy the spectrum sharing requirement in (10).

For $d_2 = 0.5$, it is obvious that with $\alpha > \alpha^* = 0.67$, we have $P_{\text{out}}^p < P_{\text{out}}^n$ and the outage probability floor of P_{out}^p is lower than P_{out}^n. Thus, we are able to satisfy the spectrum sharing requirement in (10). Furthermore, P_{out}^s achieves reasonable values (except when α is close to 1) which indicates that with our proposed spectrum sharing scheme, the secondary system is able to gain secondary spectrum access while providing the primary system a significant performance gain in terms of outage probability. Although not shown in Fig. 4, with $d_2 < 0.5$, both primary and secondary systems achieve even better outage performance.

In Fig. 5, we show the effect of P_s and d_5 on the outage performance of the primary and secondary systems. Again, we assume $R_{pt} = R_{st} = 1$ and $\nu = 4$. Here we choose $\alpha = \widehat{\alpha} = 0.75$, and fix $d_2 = d_3 = d_4 = 0.5$. We consider two different values for d_5. For each case, we fix $\frac{P_p}{\sigma^2} = 20$ dB and vary $\frac{P_s}{\sigma^2}$ from 10 dB to 30 dB.

From Fig. 5, we can again observe that the theoretical results for P_{out}^s agree well with the simulation results, and the small gap between the theoretical and simulation results for P_{out}^p when P_s is small comes from the approximation we made in (7), which holds better for large P_s. It can be observed that while P_{out}^p is independent of d_5 and P_s (for $P_s \gg \sigma^2$), P_{out}^s is significantly affected by both P_s and d_5. Specifically, when $d_5 = 0.1$ which corresponds to the scenario where ST and SR are located close to each other, the ST→SR channel gain is high and $\Pr\{R_5 < R_{st}\} \rightarrow 0$. Thus $P_{\text{out}}^s \approx 1 - \exp\left(-\frac{\sigma^2(d_2^\nu + d_3^\nu)\rho_1}{P_p}\right)$ which is independent of P_s. On the other hand, when $d_5 = 0.5$, the outage probability $\Pr\{R_5 < R_{st}\}$ is not negligible and by increasing P_s, $\Pr\{R_5 < R_{st}\}$ decreases significantly, causing a decrease in P_{out}^s which finally converges to $1 - \exp\left(-\frac{\sigma^2(d_2^\nu + d_3^\nu)\rho_1}{P_p}\right)$. We note that in the case where d_5 is small, very low outage probability P_{out}^s can be achieved, even with a small value of P_s, without affecting the outage performance of the primary system.

IV. CONCLUSIONS

We presented a protocol where a secondary transmitter applies decode-and-forward relaying to transmit the primary signal along with its own secondary signal, such that the outage performance of the primary system is not affected. We derived a critical distance from the primary transmitter to the secondary transmitter. A secondary transmitter within this critical distance can properly choose the fraction of the transmit power to be allocated for relaying the primary signal so as to meet the outage probability requirement of the primary system, and at the same time achieves secondary spectrum access.

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