Secondary Spectrum Sharing in Primary Multicasting Systems

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***Abstract*—We propose a cognitive relaying protocol with primary multicasting systems, where a primary transmitter broadcasts a common message to K licensed primary receivers. It typically adjusts its transmission rate to the user suffering from the worst channel condition in order to serve all the users simultaneously. In the limit of a large number of multicast receivers, cooperation is shown to effectively overcome this problem. In this paper, an unlicensed secondary system acts as a relay for the primary receivers. Furthermore, the secondary system achieves spectrum sharing by superimposing the secondary transmission on primary signals. We show that there exists a power allocation threshold above which the cognitive relaying protocol is able to provide better (or at least an equal) outage performance for the primary system and, at the same time, to enable the secondary system to have an opportunity to access the spectrum.**

Keywords - Cognitive system; primary multicast system; superposition coding

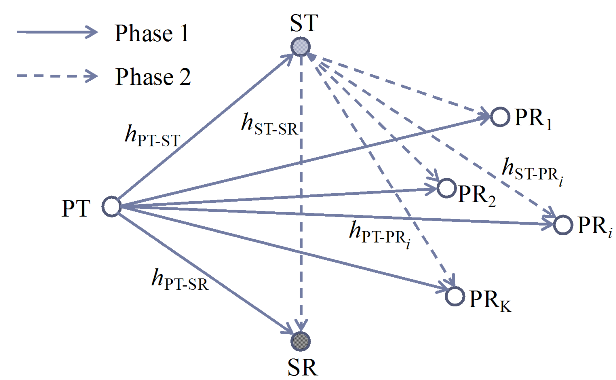

Fig. 1. System model

I. Introduction

Wireless multicast networks consist of a single transmitter node (i.e., the base station) delivering a message to multiple receiver nodes, e.g., in radio and television broadcasting. Recently, multicast applications over various wireless networks have become popular [1]-[4]. However, multicast networks typically adjust transmission rate to the user suffering from the worst channel condition in order to serve all the receivers simultaneously. As the demand on the high data rate grows, service coverage problem in multicast networks arises. It is of critical importance to design reliable wireless multicast techniques.

Many techniques have been proposed in the literature to combat channel fading in wireless multicast networks, e.g., retransmissions [5], error-correcting codes [6], and cooperation among receivers [7], [8]. Among them, cooperative multicast has recently attracted much attention, which motivates the protocol proposed in the paper. Furthermore, cooperative multicast can allow the source to transmit at a higher rate by letting receivers help each other forward messages to exploit the spatial diversity and enhance the reliability of wireless multicast. Cooperative multicast system using superposition coding (SC) [9] has been proposed to enhance the data rate with power allocation. The work in [10] proposes an outage probability tradeoff between unicast and multicast system.

We expand a wireless cooperative multicast system to cognitive relaying network in this paper. As many literatures have shown, cognitive radios can improve spectral efficiency by allowing secondary users to share resources with primary users. Also, secondary system obtains the opportunity for its transmission [11]-[15].

In this paper, we propose a spectrum sharing protocol based on superposition coding at secondary transmitter which acts as a relay for the primary multicast system as shown in Fig. 1. With this protocol, we show that the performance of the primary system can be either maintained to be the same as the case without cooperation or improved to a desired target. Furthermore, the secondary system has the opportunity for its own transmission by relaying the primary signal.

The remainder of the paper is organized as follows. Section II presents the system model. Section III derives the outage probability of the primary and secondary systems. Simulation results are presented in Section IV. Section V concludes the paper.

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II. SYSTEM MODEL

We consider a wireless network with the coexistence of primary and secondary systems. In the primary system, a primary transmitter (PT) broadcasts data to K primary receivers (PRs). The secondary system, consisting of a secondary transmitter (ST) and secondary receiver (SR), can only operate when ST would act as a relay of the primary users so as to share the spectrum as in Fig. 1. The secondary system has not been allocated the channel but is allowed to access the primary user's channel for sending its own data to SR only if it does not reduce the performance of the primary system.

When ST is involved, PT and ST collaboratively work on the following two-phase transmission. Let x_p and x_s be complex symbol vectors for the messages transmitted by PT and ST, respectively. Let h_{A-B} be the complex channel coefficients between link A and B as shown in Fig. 1. The channels are assumed to be static during the two-phase transmission:

Phase 1: PT broadcasts the signal x_p with transmit power P_p, which are received by PR_i $(i \in \{1, 2, \cdots, K\})$, ST and SR simultaneously. Let η_{PR_i}, η_{ST} and η_{SR} be the noises at PR_i, ST and SR, respectively. Then PR_i, ST and SR receive

$$\mathrm{y}_{\mathrm{PR}_i}^{(1)} = h_{\mathrm{PT-PR}_i}\sqrt{P_p}\mathrm{x}_p + \eta_{\mathrm{PR}_i}, \tag{1}$$

$$\mathrm{y}_{\mathrm{ST}}^{(1)} = h_{\mathrm{PT-ST}}\sqrt{P_p}\mathrm{x}_p + \eta_{\mathrm{ST}}, \tag{2}$$

$$\mathrm{y}_{\mathrm{SR}}^{(1)} = h_{\mathrm{PT-SR}}\sqrt{P_p}\mathrm{x}_p + \eta_{\mathrm{SR}}, \tag{3}$$

respectively, where superscript (1) denotes the first phase. ST is going to relay x_p in the following phase. PRs just keep received signal $\mathrm{y}_{\mathrm{SR}}^{(1)}$ in memory without any manipulation.

Phase 2: After reception in the first phase, the primary signal is then regenerated at ST and superimposed with the secondary signal. A fraction α, where $0 < \alpha < 1$, of the total power at ST is allocated to the primary signal, with the remaining power assigned to the secondary signal. Let P_s be transmit power of ST. ST then transmits a composite signal $\mathrm{x}_c = \sqrt{\alpha P_s}\mathrm{x}_p' + \sqrt{(1-\alpha)P_s}\mathrm{x}_s$, where signal x_p' contains identical information as x_p from phase 1 but is re-encoded with a different codebook, and α denotes the coefficient of power allocation to the PT's signal. PR_i and SR respectively receive the signals

$$\mathrm{y}_{\mathrm{PR}_i}^{(2)} = h_{\mathrm{ST-PR}_i}\left(\sqrt{\alpha P_s}\mathrm{x}_p' + \sqrt{(1-\alpha)P_s}\mathrm{x}_s\right) + \eta_{\mathrm{PR}_i}, \tag{4}$$

$$\mathrm{y}_{\mathrm{SR}}^{(2)} = h_{\mathrm{ST-SR}}\left(\sqrt{\alpha P_s}\mathrm{x}_p' + \sqrt{(1-\alpha)P_s}\mathrm{x}_s\right) + \eta_{\mathrm{SR}}, \tag{5}$$

where superscript (2) denotes the second phase. At PR, a maximum ratio combination (MRC) of the received signals in the two transmission phases in applied to decode the primary signal. SR locally generates x_p' from x_p of phase 1, subtracts it from $\mathrm{y}_{\mathrm{SR}}^{(2)}$ and finally obtains x_s from

$$\mathrm{y}_{\mathrm{SR}} = h_{\mathrm{ST-SR}}\sqrt{(1-\alpha)P_s}\mathrm{x}_s + \eta_{\mathrm{SR}}. \tag{6}$$

We assume that η_{PR_i}, η_{ST} and η_{SR} are the complex additive Gaussian noises with $\mathcal{CN}\left(0, \sigma^2\right)$[1]. We also assume that the transmitted symbols have $E[\mathrm{x}_p] = E[\mathrm{x}_p'] = E[\mathrm{x}_s] = 0$ and $E[|\mathrm{x}_p|^2] = E[|\mathrm{x}_p'|^2] = E[|\mathrm{x}_s|^2] = 1$. We have $h_{\mathrm{A-B}} \sim \mathcal{CN}\left(0, d_{\mathrm{A-B}}^{-\nu}\right)$, where ν is the path loss exponent and $d_{\mathrm{A-B}}$ is the distance between the respective link A and B. We also denote $\gamma_{\mathrm{A-B}} = |h_{\mathrm{A-B}}|^2$, for notational simplicity, and transmit SNRs $\frac{P_p}{\sigma^2} = \rho_p$, $\frac{P_s}{\sigma^2} = \rho_s$.

[1] $\mathcal{CN}\left(m, \sigma^2\right)$ denotes a complex circularly symmetric Gaussian distribution with mean m and variance σ^2.

III. THE PERFORMANCE ANALYSIS OF PRIMARY AND SECONDARY SYSTEMS

A. Primary Outage Probability With Cooperation

In the first phase, as shown by the solid lines in Fig.1, the achievable rate for links $\mathrm{PT-ST}$ and $\mathrm{PT-SR}$ can be obtained as

$$R_{\mathrm{PT-B}} = \frac{1}{2}\log_2\left(1 + \rho_p\gamma_{\mathrm{PT-B}}\right), \tag{7}$$

where the factor 1/2 accounts for the fact that the overall transmission is split into two phases and $B \in \{ST, SR\}$. If ST successfully decodes the primary signal, ST can obtain a composite signal x_c. Then in phase 2, x_c is broadcast by ST. Thus at PR_i, $\mathrm{y}_{\mathrm{PR}_i}^{(1)}$ and $\mathrm{y}_{\mathrm{PR}_i}^{(2)}$ are combined by MRC. The corresponding achievable rate between PT and PR_i, conditioned on the successful decoding at ST, is given by

$$R_{\mathrm{PT-PR}_i}^{\mathrm{MRC}} = \frac{1}{2}\log_2\left(1 + \rho_p\gamma_{\mathrm{PT-PR}_i} + \frac{\alpha\rho_s\gamma_{\mathrm{ST-PR}_i}}{(1-\alpha)\rho_s\gamma_{\mathrm{ST-PR}_i} + 1}\right) \tag{8}$$

The primary outage probability is the probability that the transmitted message with a given target rate R_{pt}, is not correctly decoded by at least one primary receiver at the end of both phases. Thus the overall outage probability of the primary system with cooperation is given by

$$\begin{aligned} P_{out,p}^{\mathrm{co}} = 1 &- \Pr\left\{R_{\mathrm{PT-ST}} > R_{pt}\right\} \\ &\times \prod_{i=1}^{K}\Pr\left\{R_{\mathrm{PT-PR}_i}^{\mathrm{MRC}} > R_{pt}\right\} \\ &- \Pr\left\{R_{\mathrm{PT-ST}} < R_{pt}\right\} \\ &\times \prod_{i=1}^{K}\Pr\left\{\frac{1}{2}R_{\mathrm{PT-PR}_i} > R_{pt}\right\}, \end{aligned} \tag{9}$$

where $R_{\mathrm{PT-PR}_i} = \log_2\left(1 + \rho_p\gamma_{\mathrm{PT-PR}_i}\right)$ for the direct link from PT to PR_i. Since $\gamma_{\mathrm{A-B}} \sim \mathcal{E}\left(d_{\mathrm{A-B}}^{\upsilon}\right)$[2], we have

$$\begin{aligned} \Pr\left\{\frac{1}{2}R_{\mathrm{PT-PR}_i} > R_{pt}\right\} &= \Pr\left\{\gamma_{\mathrm{PT-PR_i}} > \frac{\mu_p}{\rho_p}\right\} \\ &= \exp\left(-d_{\mathrm{PT-PR}_i}^{\upsilon}\frac{\mu_p}{\rho_p}\right), \end{aligned} \tag{10}$$

$$\begin{aligned} \Pr\left\{R_{\mathrm{PT-ST}} > R_{pt}\right\} &= \Pr\left\{\gamma_{\mathrm{PT-ST}} > \frac{\mu_p}{\rho_p}\right\} \\ &= \exp\left(-d_{\mathrm{PT-ST}}^{\upsilon}\frac{\mu_p}{\rho_p}\right), \end{aligned} \tag{11}$$

[2] $\mathcal{E}\left(\lambda\right)$ denotes an exponential distribution with parameter λ.

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

Assuming $\rho_s \gg 1$, we obtain

$$\begin{aligned}
&\Pr\left\{R^{\mathrm{MRC}}_{\mathrm{PT-PR}_i} > R_{pt}\right\}\\
&\approx \Pr\left\{\frac{1}{2}\log_2\left(1+\rho_p\gamma_{\mathrm{PT-PR}_i}+\frac{\alpha}{1-\alpha}\right) > R_{pt}\right\}\\
&= \begin{cases}\exp\left(-d^{\upsilon}_{\mathrm{PT-PR}_i}\frac{1}{\rho_p}\left(\mu_p-\frac{\alpha}{1-\alpha}\right)\right), & 0<\alpha<\hat{\alpha},\\ 1, & \hat{\alpha}\le\alpha<1,\end{cases}
\end{aligned} \tag{12}$$

where $\hat{\alpha} = \frac{\mu_p}{1+\mu_p}$.

In non-cooperative scenario where the secondary system does not exist, the PT transmits the data x_p to all PR's in one hop. The outage probability of the primary system without cooperative relaying is then computed as follows:

$$P^{\mathrm{no}}_{out,p} = 1 - \prod_{i=1}^{K} \Pr\left\{R_{\mathrm{PT-PR}_i} > R_{pt}\right\}. \tag{13}$$

Spectrum sharing requires that the outage probability of the primary system with the cooperative protocol is equal to or lower than the case of non-cooperative scenario, i.e.

$$P^{\mathrm{co}}_{out,p} \le P^{\mathrm{no}}_{out,p}\ . \tag{14}$$

We want to find an optimal power allocation factor α, but it cannot be solved in closed form; therefore we evaluate the outage probability numerically in Section IV. It is worth that the case of independent and identically distribution (i.i.d.) is evaluated.

B. I.i.d. Case

Consider the model where the primary receivers are close to each other. We further assume that all channel gains from PT to PR's are independent and identically distributed (i.i.d.), $\mathcal{CN}\left(0, d^{-\nu}_{\mathrm{PT-PR}}\right)$. Then we rewrite (13) as

$$P^{\mathrm{no}}_{out,p} = 1 - \exp\left(-d^{\nu}_{\mathrm{PT-PR}}\frac{\mu}{\rho_p}\right)^K, \tag{15}$$

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

From (12), we consider the spectrum sharing requirement in (14) for the following two cases.
Case 1: $\hat{\alpha} \le \alpha < 1$.

Then we rewrite (9) as

$$\begin{aligned}
P^{\mathrm{co}}_{out,p} \approx 1 &- \exp\left(-d^{\upsilon}_{\mathrm{PT-ST}}\frac{\mu_p}{\rho_p}\right)\\
&- \left[1-\exp\left(-d^{\upsilon}_{\mathrm{PT-ST}}\frac{\mu_p}{\rho_p}\right)\right]\\
&\times \exp\left(-d^{\upsilon}_{\mathrm{PT-PR}}\frac{\mu_p}{\rho_p}\right)^K.
\end{aligned} \tag{16}$$

Substituting (16) and (15) into (14), we obtain

$$d_{\mathrm{PT-ST}} \le \left[\frac{\rho_p}{\mu_p}\ln\left(\mathcal{G}^{-1}\right)\right]^{\frac{1}{\nu}} \triangleq d^{*}_{\mathrm{PT-ST}}, \tag{17}$$

where

$$\mathcal{G} = \frac{\exp\left(-d^{\nu}_{\mathrm{PT-PR}}\frac{\mu}{\rho_p}\right)^K - \exp\left(-d^{\nu}_{\mathrm{PT-PR}}\frac{\mu_p}{\rho_p}\right)^K}{1-\exp\left(-d^{\nu}_{\mathrm{PT-PR}}\frac{\mu_p}{\rho_p}\right)^K}.$$

Thus, as long as $d_{\mathrm{PT-ST}} \le d^{*}_{\mathrm{PT-ST}}$ and $\hat{\alpha} \le \alpha < 1$, we can achieve secondary transmission while satisfying (14). Also we can observe from (16), when $\alpha \ge \hat{\alpha}$, $P^{\mathrm{co}}_{out,p}$ becomes independent of α and attains a constant minimum value.
Case 2: $0 < \alpha < \hat{\alpha}$.

In this case, we rewrite (9) as

$$\begin{aligned}
P^{\mathrm{co}}_{out,p} \approx 1 &- \underbrace{\exp\left(-d^{\upsilon}_{\mathrm{PT-ST}}\frac{\mu_p}{\rho_p}\right)}_{\triangleq a}\\
&\times \exp\left(-d^{\upsilon}_{\mathrm{PT-PR}}\frac{1}{\rho_p}\left(\mu_p-\frac{\alpha}{1-\alpha}\right)\right)^K\\
&- \left[1-\exp\left(-d^{\upsilon}_{\mathrm{PT-ST}}\frac{\mu_p}{\rho_p}\right)\right]\\
&\times \underbrace{\exp\left(-d^{\upsilon}_{\mathrm{PT-PR}}\frac{\mu_p}{\rho_p}\right)^K}_{\triangleq b}.
\end{aligned} \tag{18}$$

Substituting (18) and (15) into (14), we obtain

$$\alpha \ge \frac{\mu_p - \frac{\rho_p}{K d^{\nu}_{\mathrm{PT-PR}}}\ln\left(\mathcal{F}^{-1}\right)}{1+\mu_p - \frac{\rho_p}{K d^{\nu}_{\mathrm{PT-PR}}}\ln\left(\mathcal{F}^{-1}\right)} \triangleq \alpha^{*}, \tag{19}$$

where

$$\mathcal{F} = \frac{\exp\left(-d^{\nu}_{\mathrm{PT-PR}}\frac{\mu}{\rho_p}\right)^K - b + a\cdot b}{a}.$$

Note that α^{*} is monotonously increasing with respect to $d_{\mathrm{PT-ST}}$ and it is easy to show that $\alpha^{*} \le \hat{\alpha}$ (equality holds when $d_{\mathrm{PT-ST}} = d^{*}_{\mathrm{PT-ST}}$) when $d_{\mathrm{PT-ST}} \le d^{*}_{\mathrm{PT-ST}}$. Thus, as long as $d_{\mathrm{PT-ST}} \le d^{*}_{\mathrm{PT-ST}}$ and $\alpha^{*} \le \alpha < \hat{\alpha}$, (14) is satisfied with i.i.d. case.

C. Outage Probability of the Secondary System

In this subsection, we consider the processing at SR and obtain the outage probability of the secondary system. Upon receiving $\mathrm{y}^{(1)}_{\mathrm{SR}}$ at the first phase, SR attempts to decode x_p and stores the decoding result if it succeeds.

Assuming the decoding of x_p at SR in the first transmission phase is successful, the interference component can be cancelled out from (5). 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

$$R^{\mathrm{IC}}_{\mathrm{ST-SR}} = \frac{1}{2}\log_2\left\{1+(1-\alpha)\rho_s\gamma_{\mathrm{ST-SR}}\right\}. \tag{20}$$

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 with target rates R_{pt} and

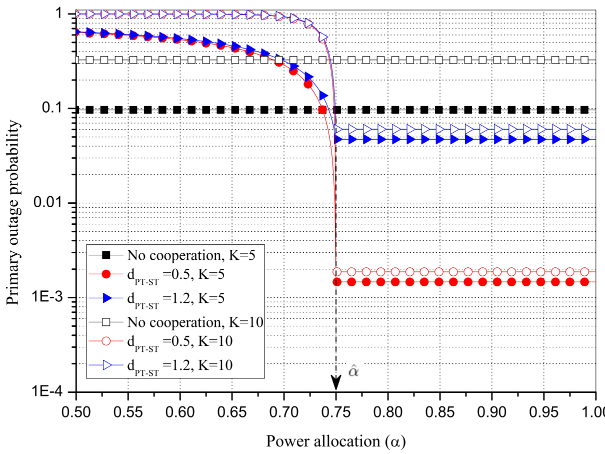

Fig. 2. Outage probability of the primary system for i.n.i.d. channels when $\rho_p = \rho_s = 20$ dB.

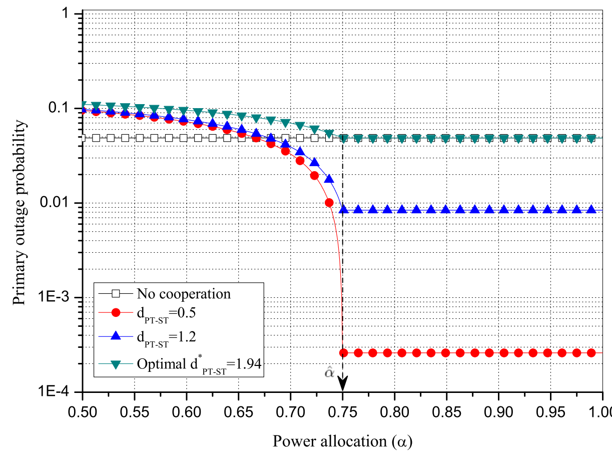

Fig. 3. Outage probability of the primary system for i.i.d. channels when $\rho_p = \rho_s = 20$ dB and $K = 5$.

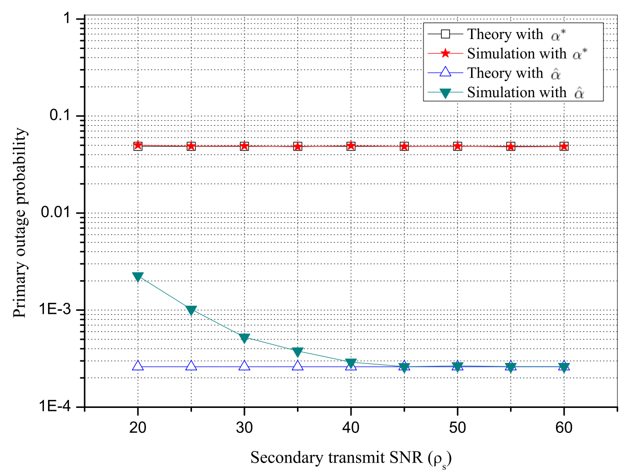

Fig. 4. Outage probability of the primary system comparison between theoretical and simulation results when i.i.d. case and $K = 5$

R_{st} for primary and secondary systems respectively, is given by

$$\begin{aligned} P_{out,s} = 1 - & \Pr\left\{R_{\mathrm{PT-ST}} > R_{pt}\right\} \\ & \times \Pr\left\{R_{\mathrm{PT-SR}} > R_{pt}\right\} \\ & \times \Pr\left\{R^{\mathrm{IC}}_{\mathrm{ST-SR}} > R_{st}\right\}, \end{aligned} \tag{21}$$

$$\begin{aligned} \Pr\left\{R^{\mathrm{IC}}_{\mathrm{ST-SR}} > R_{st}\right\} &= \Pr\left\{\gamma_{\mathrm{ST-SR}} > \frac{\mu_s}{(1-\alpha)\rho_s}\right\} \\ &= \exp\left(-d^{\nu}_{\mathrm{ST-SR}} \frac{\mu_s}{(1-\alpha)\rho_s}\right), \end{aligned} \tag{22}$$

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

IV. Simulation Results

In this section, we evaluate the outage probability of the primary and secondary systems. We choose a path loss exponent $\upsilon = 4$ and target rates $R_{pt} = R_{st} = 1$ bps/Hz in all simulations.

Fig. 2 shows the primary outage probability versus power allocation α for i.n.i.d. channel conditions when $K = 5$ and $K = 10$, respectively, with different distances from PT to ST. We assume $\rho_p = \rho_s = 20$ dB in this evaluation. We also set the distances $d_{\mathrm{PT-PR}_i} = \{0.6, 0.8, 1.0, 1.2, 1.6\}$ when $K = 5$ and $d_{\mathrm{PT-PR}_i} = \{0.2, 0.3, 0.7, 0.8, 0.9, 1.3, 1.4, 1.5, 1.8, 2\}$ when $K = 10$. It can be seen that, for both $K = 5$ and $K = 10$, the outage performance of the primary system with cooperation is still better (or equal) than the case without spectrum sharing by controlling α. Furthermore, since $\Pr\{R_{\mathrm{PT-ST}} < R_{pt}\}$ becomes larger with increasing $d_{\mathrm{PT-ST}}$, the primary outage probability for $P^{\mathrm{co}}_{out,p}$ becomes higher with increasing $d_{\mathrm{PT-ST}}$.

In Fig. 3, we consider i.i.d. channel conditions when $K = 5$. We set the distances $d_{\mathrm{PT-PR}_i} = d_{\mathrm{PT-PR}} = 1$. We show the simulation results of the primary outage probabilities for $d_{\mathrm{PT-ST}} = 0.5$, $d_{\mathrm{PT-ST}} = 1.2$, and $d_{\mathrm{PT-ST}} = d^*_{\mathrm{PT-ST}} = 1.94$ with varying the power allocation factor α. From Fig. 3, we can observe that there exists an optimal power allocation α^* which is derived from (19). When $\alpha < \hat{\alpha}(= 0.75)$, the primary outage probability $P^{\mathrm{co}}_{out,p}$ 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. However, an outage probability is independent of α when $\alpha > \hat{\alpha}$. Thus increasing α further cannot reduce the outage probability of the primary system. Finally, when $d_{\mathrm{PT-ST}} = d^*_{\mathrm{PT-ST}}$, the primary outage probability coincides with $P^{\mathrm{no}}_{out,p}$. It indicates that with $d_{\mathrm{PT-ST}} > d^*_{\mathrm{PT-ST}}$, the cooperation scheme is not able to satisfy the spectrum sharing requirement in (14). For $d_{\mathrm{PT-ST}} < d^*_{\mathrm{PT-ST}}$, i.e. $d_{\mathrm{PT-ST}} = 0.5$ and $d_{\mathrm{PT-ST}} = 1.2$, it is obvious that the outage probability of $P^{\mathrm{co}}_{out,p}$ is lower than $P^{\mathrm{no}}_{out,p}$ with $\alpha > \alpha^*(\approx 0.67)$. Thus, we are able to satisfy the spectrum sharing requirement in (14).

Comparing Figs. 2 and 3, under same conditions, the optimal power allocation value α^* which makes $P^{\mathrm{co}}_{out,p} = P^{\mathrm{no}}_{out,p}$ is different between i.n.i.d. case and i.i.d. case. The value α^* for

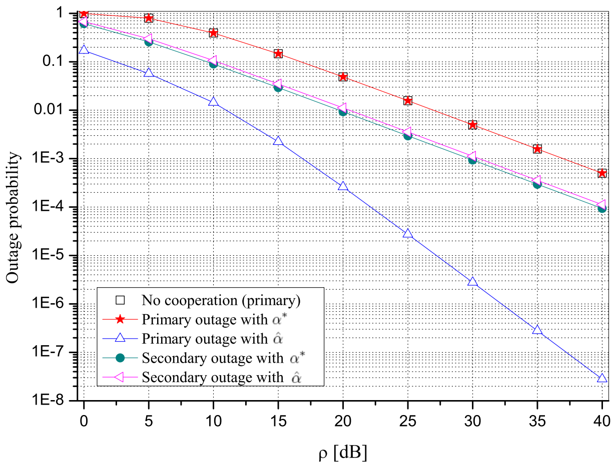

Fig. 5. Outage probability of the primary and secondary systems when i.i.d. case and $K = 5$

i.i.d case is less than one for i.n.i.d. case. In i.n.i.d. case, we allocate the $\hat{\alpha}$ even though we cannot find the optimal power fraction α^*. With the same simulation parameters, from Fig. 4, we can observe that the theoretical results agree well with the simulated ones, and the small gap between the theoretical and simulation results when ρ_s is small comes from the approximation in (12) with $\hat{\alpha}$.

In Fig. 5, we show the effects of $\rho_p = \rho_s = \rho$ on the outage performance of the primary and secondary systems. We let $d_{\mathrm{ST-SR}} = 0.5$ and the other parameters are same as ones of Fig. 2. When ST allocates a power fraction α^* for the primary system, the primary outage performance is same as the case without cooperation and the secondary system obtains an opportunity for its transmission. However, the secondary outage performance with the power fraction α^* is better than the case with $\hat{\alpha}$.

V. Conclusion

We have proposed a secondary spectrum sharing protocol using a superposition coding in primary multicasting systems. The primary multicasting system consists of a single primary transmitter and multiple primary receivers. A primary transmitter broadcasts a unique message to K primary receivers with the assistance of a secondary transmitter, which acts as a relay. A secondary transmitter applies superposition coding to transmit the primary signal along with its own signal, such that the outage performance of the primary system is not affected. By doing so, secondary system can obtain the opportunity for transmitting its own. We have shown that the outage performance of the primary and secondary systems. Furthermore, we have derived a distance of the condition for allowing secondary transmission and an optimal power fraction of the secondary transmit power in case of i.i.d. channel conditions.

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