SPECTRUM SHARING BASED ON TWO-PATH SUCCESSIVE RELAYING

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ABSTRACT

A spectrum sharing scheme is proposed for overlaid wireless networks based on the two-path successive relaying technique. In this scheme, two secondary transmitters are used to alternately transmit secondary information to their respective receivers whilst relaying the primary signal at the same time. By using superposition coding at the secondary transmitters and successive decoding at the receivers, a diversity gain of 2 is obtained for the primary system without losing the bandwidth efficiency. Outage probabilities of the primary system and secondary system are analyzed. The optimal power allocation factor of the secondary system is determined to minimize the outage probability of the secondary system while maintaining the performance of the primary system. Numerical results show that the proposed scheme can indeed enhance the outage performance of the primary and secondary systems simultaneously.

Index Terms— Cognitive radio, Relay network, Spectrum sharing.

1. INTRODUCTION

Cooperative techniques [1] are widely used in cognitive radio networks for spectrum sensing and sharing [2]. Secondary system can either implicitly access primary channel when it is idle, or explicitly help the data transmission of the primary system in exchange for the sharing of spectrum. In [3], a cooperative spectrum sharing scheme was proposed that requires three phases for the secondary system to relay the primary information and transmit its own information. Two-phase cooperative spectrum sharing schemes were presented in [4] [5], where in the first phase the primary signal is broadcasted and in the second phase the transmission of secondary signal and the relaying of primary signal is simultaneously performed. As multiple phases are required to transmit the same primary signal, spectrum efficiency of the primary system is relatively low.

To address the problem of low spectrum efficiency in relay cooperation, the two-path successive relaying scheme was proposed in [6] [7], which can achieve both cooperative diversity and high bandwidth efficiency. In this scheme, the two relays alternately help forward the source signal to the destination while the source continues its signal transmission without the need of waiting or retransmission. It was recently shown that full diversity and full rate can be achieved with the cooperation of the two relays via space-time coding techniques [8] [9]. Moreover, the achievable rate of the two path successive relaying scheme was investigated in [10], and the diversity-multiplexing tradeoff with amplify-and-forward and decode-and-forward fashion were analyzed in [11] and [12], respectively.

In this paper, to facilitate spectrum sharing of overlaid wireless networks, a two-path successive cognitive relaying scheme is developed for cognitive radio network. While two cognitive transmitters serve as relays to help primary system in a successive fashion, they also send their own information to the intended receivers, respectively. It is achieved by employing superposition coding at secondary transmitters and successive decoding at the receivers. On one hand, the secondary signal transmission introduces interference to the primary system. On the other hand, the secondary users relay the primary signals to achieve a diversity gain of 2. By determining an optimal power allocation between relaying primary signal and transmitting secondary signal, the interference imposed on the primary system can be greatly suppressed by taking advantage of cooperation. Numerical results show that the outage performance of both primary and secondary systems are improved.

The rest of this paper is organized as follows. In Section 2, system model is introduced and a spectrum sharing based on two-path successive relaying scheme is proposed. Section 3 analyzes the outage performance of the scheme for secondary and primary systems. Numerical results are given in Section 4. Section 5 concludes this paper.

2. SYSTEM MODEL

We consider an overlaid wireless network as shown in Fig. 1, where a pair of primary transmitter (PT) and receiver (PR) coexist with two pairs of secondary transmitters ($ST_i, i = 0, 1$) and receivers ($SR_i, i = 0, 1$). The positions of all nodes are fixed. The small-scale distance between any two secondary users is assumed to be much shorter than the large-scale distance between any primary user and any secondary user. The channel between any transmitter and receiver is assumed to undergo independent Rayleigh block fading, which remains unchanged in one data frame but changes independently from one frame to another. The Rayleigh fading channel from transmitter u to receiver v is denoted by $h_{u,v}$. The channel power gain is denoted by $\mathcal{G}_{u,v} = |h_{u,v}|^2$, which is exponentially distributed with mean $\bar{\mathcal{G}}_{u,v} = d_{u,v}^{-\alpha}$, where $d_{u,v}$ is the distance between u and v and α is the path loss exponent. The channel between u and v is symmetric, i.e. $h_{u,v} = h_{v,u}$. For each link, the channel is perfectly known at the receiver only.

2.1. Cognitive Relay for Spectrum Sharing

PT sends its signal continuously to PR, while ST_0 and ST_1 alternately send their own signals to their intended receivers, respectively. The transmission power of the primary and secondary system is de-

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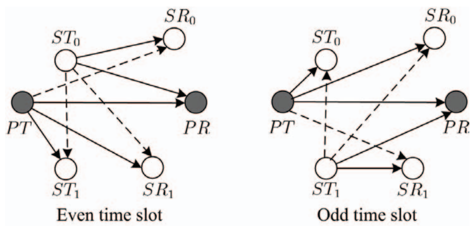

Fig. 1. Spectrum sharing based on two-path successive relay.

noted by P_p and P_s, respectively. Due to the concurrent transmission of secondary signal, the primary user is interfered. In order to remedy the impairment of the interference imposed on the primary user, ST_0 and ST_1 also help relay the primary signals by employing a two-path successive relay technique. When the primary signal is correctly received by both ST_0 and ST_1, the secondary transmitters will use superposition coding to encode their own signals along with the primary signals and then alternately forward them to PR and the secondary receivers. If at least one ST fails to receive the primary signal, both ST_0 and ST_1 will keep silent. From the perspective of information theory, the signal is said to be correctly received if the channel capacity is larger than the transmission rate. Throughout the paper, we fix the transmission rate of the primary system and secondary system as r_0 and r_1, respectively.

To expound the proposed spectrum sharing scheme with two-path successive relay, we consider the signal transmission during L time slots as below.

- *Time slot 1*: PT transmits $x_p[1]$; ST_0, SR_0, SR_1 receive and detect $x_p[1]$; ST_1 keeps silent; PR receives $x_p[1]$.
- *Time slot 2*: PT transmits $x_p[2]$; ST_0 applies the superposition coding and then transmits the composite signal $x_c[2] = f(x_p[1], x_0[2])$; SR_0 and SR_1 first cancel $x_p[1]$, then detect and cancel $x_0[2]$, and finally detect $x_p[2]$; ST_1 first detects and cancels $x_p[1]$, then detects and cancels $x_0[2]$, and finally detects $x_p[2]$; PR receives $x_p[2]$ and $x_c[2]$.
- *Time slot 3*: PT transmits $x_p[3]$; ST_1 uses the superposition coding and then transmits the composite signal $x_c[3] = f(x_p[2], x_1[3])$; SR_0 and SR_1 first cancel $x_p[2]$, then detect and cancel $x_1[3]$, and finally detect $x_p[3]$; ST_0 first detects and cancels $x_p[2]$, then detects and cancels $x_1[3]$, and finally detects $x_p[3]$; PR receives $x_p[3]$ and $x_c[3]$.
- The progress of *Time slot 2* and *3* repeats till *Time slot L*.
- *Time slot L+1*: ST_1 transmits the composite signal $x_c[L+1] = f(x_p[L], x_1[L+1])$; SR_1 cancels $x_p[L]$, then detects $x_1[L+1]$; ST_0 and SR_0 are silent; PR receives $x_c[L+1]$ and then jointly decodes the primary signals $x_p[1], x_p[2], \cdots, x_p[L]$ once by regarding secondary signals as interference.

It can be seen that totally $L+1$ time slots are used to transmit L primary symbols. The spectral efficiency of the primary system is $L/(L+1)$, which approaches 1 for large L.

2.2. Signal Model

We consider time slot k ($k = 2, ..., L$), when ST_i ($i = \mathrm{mod}(k, 2)$) and PT simultaneously do the transmissions. For ST_i, the transmitted composite signal is generated by linearly combining the previous primary signal and its current secondary signal, e.g.,

$$x_c[k] = f(x_p[k-1], x_i[k]) = \sqrt{\beta}x_p[k-1] + \sqrt{1-\beta}x_i[k], \quad (1)$$

where $\beta \in [0, 1]$ is the power allocation factor, which is the same for both ST_0 and ST_1. If $\beta = 0$, ST_i becomes selfish and only transmits its own signal. If $\beta = 1$, ST_i is selfless and only relays the primary signal. We set $\beta \geq 0.5$ because more power is allocated to relay the primary signal and less interference is introduced.

The signal received by SR_i and SR_j in time slot k is written as $y_{SR_v}[k]$ ($v = i$ or j),

$$\begin{aligned} y_{SR_v}[k] &= \sqrt{P_p}h_{PT,SR_v}x_p[k] + \sqrt{P_s}h_{ST_i,SR_v} \\ &\quad \times \left(\sqrt{\beta}x_p[k-1] + \sqrt{1-\beta}x_i[k]\right) + n_{SR_v}[k]. \end{aligned} \quad (2)$$

The desired signal for SR_i is $x_i[k]$. However, both SR_i and SR_j need to have $x_p[k]$ for the interference cancelation in the next time slot. Hence, the successive decoding is performed as follows. First, the previous primary signal $x_p[k-1]$ is canceled. Then, the secondary signal $x_i[k]$ is detected and canceled. Finally, the current primary signal $x_p[k]$ is detected.

The signal received by another secondary transmitter ST_j ($j = 1 - i$) is given by

$$\begin{aligned} y_{ST_j}[k] &= \sqrt{P_p}h_{PT,ST_j}x_p[k] + \sqrt{P_s}h_{ST_0,ST_1} \\ &\quad \times \left(\sqrt{\beta}x_p[k-1] + \sqrt{1-\beta}x_i[k]\right) + n_{ST_j}[k]. \end{aligned} \quad (3)$$

The secondary transmitter ST_j needs to know the current primary signal $x_p[k]$ for the relaying in the next time slot. As the secondary users are close to each other, the channel between ST_0 and ST_1 is stronger than the channel between PT and ST_j. Hence, the composite signal $x_c[k]$ can be firstly detected and canceled. Then, the current primary signal is detected. In the detection of $x_c[k]$, as $\beta > 0.5$ the previous primary signal $x_p[k-1]$ is firstly detected and canceled, and then the secondary signal $x_i[k]$ is extracted.

For the primary receiver PR, all the received signals in $L+1$ time slots are written as a vector $\mathbf{y}$ as follows.

$$\mathbf{y} = \mathbf{H}\mathbf{x}_p + \mathbf{w}, \quad (4)$$

where $\mathbf{x}_p = [x_p[1], x_p[2], \cdots, x_p[L]]^{\mathcal{T}}$ is the primary signal, and $\mathbf{H}$ is the equivalent MIMO channel with size $(L+1) \times L$, given by

$$\begin{bmatrix} c_{PT,PR} & 0 & \cdots & 0 & 0 & 0 \\ c_{ST_0,PR} & c_{PT,PR} & \ddots & 0 & 0 & 0 \\ 0 & c_{ST_1,PR} & \ddots & 0 & 0 & 0 \\ \vdots & \ddots & \ddots & \ddots & \ddots & \vdots \\ 0 & 0 & \ddots & c_{ST_1,PR} & c_{PT,PR} & 0 \\ 0 & 0 & \cdots & 0 & c_{ST_0,PR} & c_{PT,PR} \\ 0 & 0 & \cdots & 0 & 0 & c_{ST_1,PR} \end{bmatrix}$$

where $c_{PT,PR} = \sqrt{P_p}h_{PT,PR}$, $c_{ST_0,PR} = \sqrt{\beta P_s}h_{ST_0,PR}$, $c_{ST_1,PR} = \sqrt{\beta P_s}h_{ST_1,PR}$. The vector $\mathbf{w}$ denotes the interference plus the noise, given by

$$\mathbf{w} = \sqrt{(1-\beta)P_s}\begin{bmatrix} 0 \\ h_{ST_0,PR}x_0[2] \\ h_{ST_1,PR}x_1[3] \\ \vdots \\ h_{ST_0,PR}x_0[L] \\ h_{ST_1,PR}x_1[L+1] \end{bmatrix} + \begin{bmatrix} n_{PR}[1] \\ n_{PR}[2] \\ n_{PR}[3] \\ \vdots \\ n_{PR}[L] \\ n_{PR}[L+1] \end{bmatrix}$$

Obviously, a diversity gain of 2 is achieved for the primary system because each primary signal passes through two independent fading channels.

3. PERFORMANCE ANALYSIS

Let the event of both secondary transmitters correctly detecting the primary signal be E_c. In such case, the two-path successive relaying will be properly activated. Otherwise, the secondary transmitters will keep silent. The outage probabilities of the primary and secondary system are denoted by P^P_{out} and P^S_{out}, respectively. Then,

$$P^P_{\text{out}} = \Pr(E_c)P^P_{\text{out-c}} + [1-\Pr(E_c)]\,P^P_{\text{out-d}}, \quad (5)$$
$$P^S_{\text{out}} = \Pr(E_c)P^S_{\text{out-c}} + [1-\Pr(E_c)]\,P^S_{\text{out-d}}, \quad (6)$$

where $P^P_{\text{out-c}}$ and $P^S_{\text{out-c}}$ represent the outage probabilities of the primary system and secondary system using two-path successive relay, respectively. $P^P_{\text{out-d}}$ and $P^S_{\text{out-d}}$ denote the outage probabilities of the primary system and secondary system with secondary transmitters being silent. As the secondary system keeps silent in this case, it has $P^S_{\text{out-d}} = 1$.

3.1. The Occurrence Probability $\Pr(E_c)$

For ST_i, before detecting the current primary signal, the previous primary signal forwarded from ST_j $(j = 1-i)$ should first be located and canceled. To correctly detect the previous primary signal, it requires the transmission rate r_0 be no larger than the achievable rate $R^1_{ST_i}$, which is given by

$$R^1_{ST_i} = \log_2\left(1 + \frac{\beta\rho\eta\mathcal{G}_{ST_0,ST_1}}{\eta\mathcal{G}_{PT,ST_i} + (1-\beta)\rho\eta\mathcal{G}_{ST_0,ST_1} + 1}\right), \quad (7)$$

where the numerator is the power of the previous primary signal, and the denominator represents the power of interference plus noise. In particular, $\eta = P_p/N_0$ and $\rho = P_s/P_p$.

After the successful detection and cancelation of the previous primary signal, the current secondary signal is detected and canceled. To guarantee the correct detection of the current secondary signal, it would require r_1 be no larger than the achievable rate $R^2_{ST_i}$, which is given by

$$R^2_{ST_i} = \log_2\left(1 + \frac{(1-\beta)\rho\eta\mathcal{G}_{ST_0,ST_1}}{\eta\mathcal{G}_{PT,ST_i} + 1}\right). \quad (8)$$

After the successful detection and cancelation of the secondary signal, the achievable rate of the current primary signal becomes

$$R^3_{ST_i} = \log_2\left(1 + \eta\mathcal{G}_{PT,ST_i}\right). \quad (9)$$

Based on the above analysis, the occurrence probability of the two-path successive relaying process being activated is

$$\begin{aligned}\Pr(E_c) = \Pr\big\{&R^1_{ST_0} \geq r_0, R^2_{ST_0} \geq r_1, R^3_{ST_0} \geq r_0,\\ &R^1_{ST_1} \geq r_0, R^2_{ST_1} \geq r_1, R^3_{ST_1} \geq r_0\big\}\end{aligned} \quad (10)$$

3.2. Outage Probability of the Primary System

The rate for direct transmission between PT and PR without relay is $R_{pd} = \log_2(1 + \eta\mathcal{G}_{PT,PR})$. Then, the outage probability is given by,

$$P^P_{\text{out-d}} = \Pr\{R_{pd} < r_0\} = 1 - \exp[-T/\eta], \quad (11)$$

where $T = 2^{r_0} - 1$. Distance between any two nodes is normalized with respect to the distance between PT and PR, so $d_{PT,PR} = 1$.

For two-path successive relaying, according to the equivalent MIMO signal model (4), the rate of the primary system is [11]

$$R_{pc} = \frac{1}{L+1}\log_2\left[\det(\mathbf{I}_{L+1} + \tilde{\mathbf{H}}\tilde{\mathbf{H}}^{\mathcal{H}})\right], \quad (12)$$

where $\tilde{\mathbf{H}} = \mathbf{C}^{-\frac{1}{2}}\mathbf{H}$ is the normalized channel matrix, with $\mathbf{C} = \mathbb{E}[\mathbf{w}\mathbf{w}^{\mathcal{H}}] = \text{diag}\{N_0, \lambda_0, \lambda_1, ..., \lambda_0, \lambda_1\}$, where $\lambda_0 = (1-\beta)P_s\mathcal{G}_{ST_0,PR} + N_0$ and $\lambda_1 = (1-\beta)P_s\mathcal{G}_{ST_1,PR} + N_0$. The matrix in (12) is a trigonal matrix, whose determinant is not easy to obtain. But the approximate rate $\tilde{R}_{pc}$ can be obtained by dividing $\tilde{\mathbf{H}}$ into interference-free blocks with size 3×2, as follows.

$$\begin{aligned}\tilde{R}_{pc} = \frac{L}{2(L+1)}\log_2\Bigg\{&\frac{\eta x}{(1-\beta)\rho\eta y + 1}\\ &\times\left[1 + \frac{\eta x}{(1-\beta)\rho\eta z + 1}\right] + \frac{\rho\eta z + 1}{(1-\beta)\rho\eta z + 1}\\ &\times\left[\frac{\eta x}{(1-\beta)\rho\eta z + 1} + \frac{\rho\eta y + 1}{(1-\beta)\rho\eta y + 1}\right]\Bigg\},\end{aligned} \quad (13)$$

where $x = \mathcal{G}_{PT,PR}$, $y = \mathcal{G}_{ST_0,PR}$, and $z = \mathcal{G}_{ST_1,PR}$. The approximate outage probability is computed as

$$\tilde{P}^P_{\text{out-c}} = \Pr\left\{\tilde{R}_{pc} < r_0\right\} \quad (14)$$

3.3. Outage Probability of the Secondary System

Consider a certain time slot t $(2 \leq t \leq L-1)$, in which PT transmits the current primary signal and ST_i $(i = \text{mod}(t, 2))$ transmits the composite signal simultaneously. After the cancelation of the previous primary signal, SR_i should first detect its desired secondary signal by viewing the current primary signal as noise. To get the correct detection of the secondary signal, it requires r_1 be no larger than the achievable rate $R^1_{SR_i}$, which is given by

$$R^1_{SR_i} = \log_2\left(1 + \frac{(1-\beta)\rho\eta\mathcal{G}_{ST_i,SR_i}}{\eta\mathcal{G}_{PT,SR_i} + 1}\right). \quad (15)$$

In time slot $t+1$, PT and ST_j $(j = 1-i)$ will transmit at the same time. After the cancelation of the previous primary signal, the secondary receiver SR_i needs to detect and cancel the secondary signal of ST_j followed by the detection of the current primary signal. To guarantee the correct detection and cancelation of the secondary signal, the transmission rate r_1 must be no larger than the achievable rate $R^2_{SR_i}$, which is given by

$$R^2_{SR_i} = \log_2\left(1 + \frac{(1-\beta)\rho\eta\mathcal{G}_{ST_j,SR_i}}{\eta\mathcal{G}_{PT,SR_i} + 1}\right). \quad (16)$$

For any time slot, after cancelation of the secondary signal, the primary signal needs to be detected and it will be used for interference cancelation at the next time slot. This requires the transmission rate r_0 to be smaller than or equal to the achievable rate $R^3_{SR_i}$, which is given by

$$R^3_{SR_i} = \log_2\left(1 + \eta\mathcal{G}_{PT,SR_i}\right). \quad (17)$$

Therefore, the outage probability of the secondary system (ST_i, SR_i) is

$$P^{S_i}_{\text{out-c}} = 1 - \Pr\left\{R^1_{SR_i} \geq r_1, R^2_{SR_i} \geq r_1, R^3_{SR_i} \geq r_0\right\}. \quad (18)$$

Finally, we obtain

$$P^S_{\text{out-c}} = \frac{1}{2}(P^{S_0}_{\text{out-c}} + P^{S_1}_{\text{out-c}}). \quad (19)$$

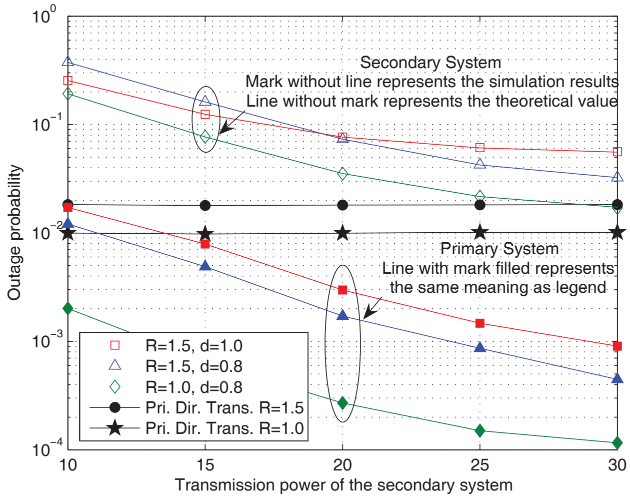

Fig. 2. Outage performance of the spectrum sharing scheme with different rates and large-scale distance.

3.4. Determining Power Allocation Factor β

According to (5), (6) and (19), the power allocation factor β can be optimized by minimizing the outage probability of the secondary system (P_{out}^{S}) without degrading the performance of the primary system ($P_{\text{out}}^{P} \leq P_{\text{out-d}}^{P}$). It can be equivalently written as

$$\begin{aligned} &\max_{\beta\in[0.5,1]} \quad \frac{1}{2}\Pr(E_c)\left[\left(1-P_{\text{out-c}}^{S_0}\right)+\left(1-P_{\text{out-c}}^{S_1}\right)\right] \\ &\text{s. t.} \quad P_{\text{out-c}}^{P} \leq P_{\text{out-d}}^{P} \end{aligned} \tag{20}$$

In the objective function, $1-P_{\text{out-c}}^{S_i}$ is the success probability of the secondary system (ST_i, SR_i), which is a monotonically decreasing function of the power allocation factor β in the whole range of $[0.5, 1]$. We notice that, the occurrence probability $\Pr(E_c)$ given by (10) is always a monotonically increasing function of β when $\max\left\{0.5, \frac{T}{T+1}\right\} \leq \beta < \max\left\{0.5, \frac{T(U+1)}{T(U+1)+U}\right\}$ and a monotonically decreasing function of β when $\max\left\{0.5, \frac{T(U+1)}{T(U+1)+U}\right\} \leq \beta < 1$ for $U = 2^{r_1}-1$. As the increasing speed of $\Pr(E_c)$ in the low range always exceeds the decreasing speed of the success probability, the maximal value of the objective function is obtained at the point $\hat{\beta} = \frac{T(U+1)}{T(U+1)+U}$. As $P_{\text{out-c}}^{P}$ monotonically decreases with β in the whole range, by letting $\tilde{P}_{\text{out-c}}^{P} = P_{\text{out-d}}^{P}$, we can find the approximate critical point $\tilde{\beta}$. The optimal power allocation factor of (20) is thus given as $\beta^* = \max\left\{\hat{\beta}, \tilde{\beta}\right\}$.

4. SIMULATION RESULTS

In the simulation of the outage probabilities of the primary system and secondary system, we set $\alpha = 3$, $L = 8$. The transmission rate $r_0 = r_1 = R$ and R is chosen as 0.5 or 1, respectively. The large-scale distance between any primary user and any secondary user is $d = 0.8$ or 1. The small-scale distance between any two secondary users is fixed as 0.1. The transmission power of the primary system is fixed as $P_p = 20$ dB.

It can be seen from Fig. 2 that, with the increase of the secondary transmission power, the performance of secondary system becomes better, while the performance of the primary system is greatly improved. The performance becomes better with the decrease of the target rate. With the increase of the large-scale distance, the performance becomes worse, because the average channel quality gets worse. Moreover, numerical results coincide well with the simulation results for the secondary system. It reveals that the proposed spectrum sharing can well improve the performance of both primary and secondary system if an optimal power allocation factor β is used. Although the secondary signal transmission will interfere primary system, the secondary system also makes contribution to the primary system by relaying the primary signals. It is a win-win solution to both primary and secondary systems.

5. CONCLUSION

A spectrum sharing scheme based on two-path successive relay was proposed in this paper. By combining the primary and secondary signals, the two secondary transmitters not only support the secondary signal transmission, but also help relay primary signal transmission via a diversity approach. The outage probabilities of the primary and secondary systems were analyzed and the optimal power allocation factor was determined. Numerical results were shown to validate the fact that the proposed spectrum sharing scheme can enhance the outage performance of both primary and secondary systems.

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