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Research Article

The Effect of Misdetection Probability on the Performance of Cooperative-Relaying-Based Cognitive Radio Systems

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Cognitive radio (CR) is a promising solution to address the more and more congested radio spectrum. Cooperative relaying can provide a better transmission performance for the secondary user (SU), while the performance of the primary user (PU, also named licensed user) should be preferentially protected especially when there is misdetection probability. In this paper, in order to keep the PU away from outage caused by the interference from the SU under a certain signal-to-noise ratio (SNR), the maximum SNR for the SU can be derived by using the rate decaying factor (RDF). Then, based on the maximum channel gain and the maximum SNR, the outage probability is analyzed using decode-and-forward (DF) relaying and amplify-and-forward (AF) relaying schemes. Numerical results show that the outage probability decreases when the power allocation factor increases for DF strategy, while the outage probability has error floor when the power allocation factor increases for AF strategy. And the relaying scheme based on the maximum channel gain outperforms that based on the maximum SNR when the power allocation factor and detection probability are small, while the relaying scheme based on the maximum SNR outperforms that based on the maximum channel gain when the power allocation factor is large. What is more, AF relaying has better outage performance in the practical implementation.

1. Introduction

In the CR system, the SUs share the PU bands. Therefore, it is a great challenge for CR systems to protect the PU signal away from the interference caused by the SU signal [1]. How to deal with the interference which is caused by the misdetection probability in the CR sensing period is a critical issue. In other words, on one hand, the performance of the SU transmission should be improved; on the other hand, the PU's transmission quality should be guaranteed. This requires the cooperative relaying with perfect sensing ability. In [2] the ideal sensing result is assumed on the PU's bands, and SUs only can communicate with each other through the common existing bands when they are not occupied by the PUs. Therefore, there will be no direct communication link which can be performed if there is no common band. The concept of cooperative relaying has been incorporated into cognitive radio system when there is no direct transmission link between two cognitive users. Cooperative transmission can maintain the SU's average throughput. The reason is that the cooperative relaying nodes provide additional spatial and spectrum diversity which improves the performance of the transmission between the source and the destination [3].

The cooperative relay has two main strategies: DF relaying and AF relaying. Cooperative communication is an efficient strategy that overcomes most of the limitations in wireless communications systems [4, 5]. Using cooperation, the users require less total power to achieve a certain throughput [4]. DF relaying uses relays to demodulate and decode the transmitted signal from the source before reencoding and retransmitting to the destination.

Related Work. In [6], a closed-form solution for the outage probability of DF relaying when the statistics of the channels between the source, relays, and destination are assumed to be independent and identically distributed was presented, while an exact closed-form expression for the outage probability of DF relaying in independent but not identically distributed dissimilar Rayleigh fading channels was derived in [7]. As a low-cost strategy, the AF relaying boosts the coverage and capacity of cellular networks, particularly in regions with signal shadowing [8]. The outage probability is a criterion of the performance evaluation for cooperative relaying. The outage probability for AF relaying using variable gain nodes is accurately calculated in [9, 10]. Variable gain relay is a kind of common AF strategy which compensates the signal fading with the instantaneous channel state information (CSI). The fixed relay is another strategy which is analyzed in [11], while the instantaneous CSI in the fixed relay is not required compared with the variable gain relay.

The capacity theorems of DF relaying and AF relaying are proposed in [12]. Reference [13] analyzes and compares the performances of AF, DF, selection DF, and incremental AF strategies. The optimal resource allocation is researched for the Gaussian parallel fading relay channel under both full duplex and half duplex where the source and relay nodes are subject to separate power constraints [14]. The power allocation is investigated in a three-node CR network after the cooperative relay in direct, dual-hop, and relay channels is studied to acquire optimal throughput [15]. In [16], in the case that the Rayleigh instantaneous channel gain is exponentially distributed and available, the optimal outage probability is achieved using power allocation under source node and select nodes. In [17], the authors derive the optimal power allocation scheme using selection amplify-and-forward (S-AF) relay nodes to maximize the capacity in Rayleigh fading channel with known complete CSI and channel statistics. The outage probabilities of DF relaying and AF relaying with different power allocation factors were analyzed in [18], while [19] analyzes the outage probability of DF relaying and AF relaying using channel gain and signal-to-noise ratio (SNR) with different time duration allocation factors. However the impact of misdetection (one is the case in which the PU occupies the bands and is detected to be busy and another is the case in which the PU occupies the bands but is detected to be free; only the second midsection can cause interference to PU) probability in spectrum sensing period on the data transmission has not been discussed.

In this paper, we propose the concept of rate decaying factor (RDF). Using RDF, the SUs maximum SNR is derived in the premise of PU transmission link without interruption under the right PUs SNR. Then, using maximum channel gain and maximum SNR schemes, we analyze and calculate the outage probabilities of DF relaying and AF relaying for the relay node under the maximum SUs SNR with different power allocation factors.

2. System Model

The failure of spectrum sensing causes the SU signal to interfere with the PU on certain spectrum bands. As depicted in Figure 1, The PU's signal is truncated by the SU's signal when the bands are occupied but detected to be free. The SU's signal is the same as PU: one is from the SU's base station and another is from the relay nodes. The SU's signal is truncated by the PU's signal when the bands are occupied but detected to be free. So the SU and PU may interfere with each other when the bands are misdetected. g_0 represents the PU direct transmission link; f_0 and f_1 represent the interference links to the PU caused by the SU signal. On the other hand, the SU may be interfered with by the PU signal when it starts to

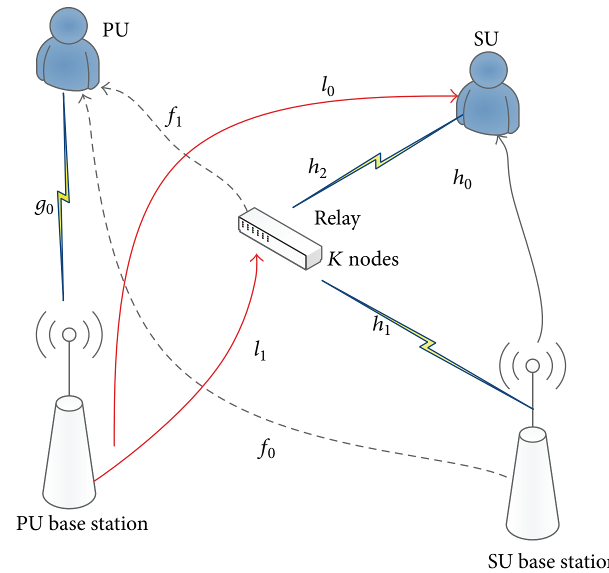

FIGURE 1: The system model.

utilize the PU spectrum bands in the case in which the PU is actually busy but is detected to be free; h_0 represents the SU direct transmission link, h_1 and h_2 represent the relaying links of the SU, and l_0 and l_1 represent the interference links to the SU caused by the PU. Furthermore, we assume the system is a full duplex system.

2.1. Decode-and-Forward Relaying Strategy. For DF strategy, there is the case that the PU is detected (P_D: PU is absent and is detected to be absent; PU is busy and is detected to be busy) or misdetected ($\overline{P_D}$; PU is absent but is detected to be busy; PU is busy but is detected to be absent). The received PU signal can be divided into two cases: one is the case in which the PU occupies bands and is detected to be busy; therefore the noise is the channel noise; the other is the case in which the PU occupies the bands but is detected to be free; thus the noises consist of not only the channel noise but also the SU signal. Considering these two cases, the received signal of PU (y_{pu}) can be represented as

$$y_{\text{pu}} = \begin{cases} g_0\sqrt{P_{\text{pu}}}x_{\text{pu}} + n_{\text{pu}}, & P_D, \\ g_0\sqrt{P_{\text{pu}}}x_{\text{pu}} + f_0\sqrt{\xi P_{\text{su}}}x_{\text{su}} + f_1\sqrt{(1-\xi)P_{\text{su}}}x_{\text{su}} + n_{\text{pu}}, & \overline{P_D}, \end{cases} \quad (1)$$

where P_{pu} is the PU transmitting power, P_{su} is the SU total transmitting power which contains the power of source node and relay nodes, x_{pu} is the PU transmitting signal, x_{su} is the SU transmitting signal, and we assume that $E\{|x_{\text{pu}}|^2\} = E\{|x_{\text{su}}|^2\} = 1$, g_0 is the average channel gain of the PU link, f_0 and f_1 are the average channel gains of interference link to the PU, n_{pu} is the PU noise, P_D is the detection probability in spectrum sensing period, and $\overline{P_D} = 1 - P_D$ is misdetection probability.

The received SU signal contains two main parts. The first part is the transmitted signal from the SU when the PU signal is absent and is actually detected to be free (P_D); the noise is only the channel noise. The second part contains not only the channel noise but also the PU signal when the PU signal is present but detected to be free ($\overline{P_D}$). Take all cases into account; the received signal from the direct link of SU (y_{su}) can be represented as

$$y_{su} = \begin{cases} \widetilde{h_0}\sqrt{\xi P_{su}}x_{su} + n_{su}, & P_D, \\ \widetilde{h_0}\sqrt{\xi P_{su}}x_{su} + l_0\sqrt{P_{pu}}x_{pu} + n_{su}, & \overline{P_D}, \end{cases} \quad (2)$$

where $\widetilde{h_0}$ is the instantaneous channel gain of the SU direct link, l_0 is the average channel gain of interference link to the SU, ξ is the SU base station (BS) power allocation factor, and n_{su} is the SU noise.

When multihop relaying is performed the received signal of the kth node (r_k) is

$$r_k = \begin{cases} \widetilde{h_1^k}\sqrt{\xi P_{su}}x_{su} + n_{h_1}, & P_D, \\ \widetilde{h_1^k}\sqrt{\xi P_{su}}x_{su} + l_1\sqrt{P_{pu}}x_{pu} + n_{h_1}, & \overline{P_D}, \end{cases} \quad (3)$$

where $\widetilde{h_1^k}$ is the instantaneous channel gain of the relay link of the SU BS-to-relay nodes, l_1 is the average channel gain value of interference link to the SU, and n_{h_1} is the receiver noise.

The received signal from the relaying link of the SU (y_{k-su}) is

$$y_{k-su} = \begin{cases} \widetilde{h_2}\sqrt{(1-\xi)P_{su}}x_{su} + n_{h_2}, & P_D, \\ \widetilde{h_2}\sqrt{(1-\xi)P_{su}}x_{su} + \widetilde{h_2}l_1\sqrt{P_{pu}}x_{pu} + l_0\sqrt{P_{pu}}x_{pu} + n_{h_2}, & \overline{P_D}, \end{cases} \quad (4)$$

where $\widetilde{h_2}$ is the instantaneous channel gain of relay link from relay node to the SU and n_{h_2} is the channel noise of relay to the SU.

2.2. Amplify-and-Forward Relaying Strategy. For AF strategy, the channel noise introduced from the relay in the receiver is not considered for simplicity; in the case in which the PU is detected (P_D) or misdetected ($\overline{P_D}$) when it is actually present, the received signal of the PU (y_{pu}) can be represented as

$$y_{pu} = \begin{cases} g_0\sqrt{\xi P_{pu}}x_{pu} + n_{pu}, & P_D, \\ g_0\sqrt{\xi P_{pu}}x_{pu} + f_0\sqrt{\xi P_{su}}x_{su} + \alpha f_1\sqrt{(1-\xi)P_{su}}x_{su} + n_{pu}, & \overline{P_D}, \end{cases} \quad (5)$$

where $\alpha = 1/h_1$ is the relay scale of AF relaying. The received signal for the kth relay node of the relay link is the same as (2).

The SU received signal of the relay link in the condition that the spectrum bands are detected and misdetected for the AF strategy can be represented as

$$y_{k-su} = \begin{cases} \alpha\widetilde{h_2}\sqrt{(1-\xi)P_{su}}x_k + n_{h_2}, & P_D, \\ \alpha\widetilde{h_2}\sqrt{(1-\xi)P_{su}}x_k + \alpha\widetilde{h_2}l_1\sqrt{P_{pu}}x_{pu} + l_0\sqrt{P_{pu}}x_{pu} + n_{h_2}, & \overline{P_D}. \end{cases} \quad (6)$$

The Scheme for Selecting Node. (1) The maximum channel gain scheme: the maximum channel gain node is selected from the relay nodes through comparing the received signals; when the maximum channel gain is larger than the direct link channel gain, the relay link is selected to transmit the signal; otherwise the direct link is selected.

(2) The maximum SNR scheme: the maximum SNR node is selected from the relay nodes through comparing the received signals; when the maximum SNR is larger than the direct link SNR, the relay link is selected to transmit the signal; otherwise the direct link is selected.

The remainder of the paper is organized as follows. The system model and the relay nodes selected scheme are proposed in Section 2. In Section 3, the SUs' maximum SNR is derived through RDF in the premise of keeping PUs away from interruption under a certain PUs' SNR; then the outage probabilities of DF relaying and AF relaying based on the selected relay node using maximum channel gain and maximum SNR with different power allocation factors are analyzed. In Section 4, numerical results are discussed. In Section 5, we draw the conclusion.

3. System Analysis

3.1. Decode-and-Forward Relaying

3.1.1. Max Channel Gain. The average SNR of the PU when using the DF strategy can be written as

$$\gamma_{DF_{aver}} = E\{SNR_{DF}\} = P_D\gamma_{DF_{P_D}} + (1-P_D)\gamma_{DF_{\overline{P_D}}}, \quad (7)$$

where we consider n_{pu}, n_{su}, n_{h_2}, and n_{h_1} are the additive white Gaussian noises (AWGN) with zero mean and variance $E\{n_{pu}, n_{su}, n_{h_1}, n_{h_2}\} = N_0$, where $E[\cdot]$ denotes the expectation. $\gamma_{DF_{P_D}}$ is the PU SNR under the probability of detection which can be written as

$$\gamma_{DF_{P_D}} = \frac{{g_0}^2 P_{pu}}{N_0} = {g_0}^2\gamma_{pu}, \quad (8)$$

γ_{su} is the SU SNR, and $\gamma_{DF_{\overline{P_D}}}$ is the PU SNR under the misdetection probability which can be written as

$$\gamma_{DF_{\overline{P_D}}} = \frac{{g_0}^2\gamma_{pu}}{1 + {f_0}^2\xi\gamma_{su} + {f_1}^2(1-\xi)\gamma_{su} + f_0 f_1\sqrt{\xi(1-\xi)}\gamma_{su}}. \quad (9)$$

The criterion to keep the PU away from interruption is $(1/2)\log(1+\gamma_{aver}) > R_{pu}^{max}$ (γ_{aver} is the average SNR considering the PU interference signal). The maximum transmission rate will be changed if the SNR changes; therefore we put forward the concept of rate decaying factor (RDF) and define the RDF as follows:

$$\eta = \frac{R_{\mathrm{pu}}^{\max}}{R_{\mathrm{pu}}}, \tag{10}$$

where $R_{\mathrm{pu}} = (1/2)\log(1+\gamma_{\mathrm{DF}_{P_D}})$ is the maximum transmission rate without SU interference and $R_{\mathrm{pu}}^{\max}$ is the maximum transmission considering the SU interference. The PU maximum transmission rate will decrease due to the interference from the SU signal.

Define the RDF value for DF strategy:

$$\eta_{\mathrm{DF}} = \frac{1}{1+P_D(1-P_D)\left[f_0^{\,2}\xi + f_1^{\,2}(1-\xi) + f_0 f_1\sqrt{\xi(1-\xi)}\right]}. \tag{11}$$

Then the maximum SU SNR can be derived using (7), (10), and (11) as

$$\gamma_{\mathrm{DF}_{\mathrm{su}}} < \frac{g_0^{\,2}\gamma_{\mathrm{pu}} - \left[\left(1+\gamma_{\mathrm{DF}_{P_D}}\right)^{\eta_{\mathrm{DF}}} - 1\right]}{\phi\left[\left(1+\gamma_{\mathrm{DF}_{P_D}}\right)^{\eta_{\mathrm{DF}}} - 1\right] - P_D g_0^{\,2}\phi\gamma_{\mathrm{pu}}}, \tag{12}$$

where $\phi = f_0^{\,2}\xi + f_1^{\,2}(1-\xi) + f_0 f_1\sqrt{\xi(1-\xi)}$. Also, for AF strategy, the RDF value can be defined as

$$\eta_{\mathrm{AF}} = \frac{1}{1+P_D(1-P_D)\left[f_0^{\,2}\xi + \alpha^2 f_1^{\,2}(1-\xi) + \alpha f_0 f_1\sqrt{\xi(1-\xi)}\right]}. \tag{13}$$

Then the maximum SU SNR is

$$\gamma_{\mathrm{AF}_{\mathrm{su}}} < \frac{g_0^{\,2}\gamma_{\mathrm{pu}} - \left[\left(1+\gamma_{\mathrm{DF}_{P_D}}\right)^{\eta_{\mathrm{AF}}} - 1\right]}{\varphi\left[\left(1+\gamma_{\mathrm{DF}_{P_D}}\right)^{\eta_{\mathrm{AF}}} - 1\right] - P_D g_0^{\,2}\varphi\gamma_{\mathrm{pu}}}, \tag{14}$$

where $\varphi = \xi f_0^{\,2} + (1-\xi)\alpha^2 f_1^{\,2} + \alpha f_0 f_1\sqrt{\xi(1-\xi)}$. We assume that the channel is a complex Gaussian channel. $\widetilde{h_0}$, $\widetilde{h_1^k}$, and $\widetilde{h_2}$ follow Gaussian distribution, sign as $\widetilde{h_0} \sim \mathrm{CN}(0,\Omega_0)$, $\widetilde{h_1^k} \sim \mathrm{CN}(0,\Omega_1^k)$, and $\widetilde{h_2} \sim \mathrm{CN}(0,\Omega_2)$, where $\mathrm{CN}(\cdot,\cdot)$ means Gaussian distribution. Therefore, $\widetilde{h_0}^2 \sim E(\Omega_0)$, $\widetilde{h_1^k}^2 \sim E(\Omega_1^k)$, and $\widetilde{h_2}^2 \sim E(\Omega_2)$.

The SU SNR of the direct link is

$$\begin{aligned}\gamma_{b-\mathrm{su}} &= E\left\{\mathrm{SNR}_{b-\mathrm{su}}\right\}\\ &= P_D\widetilde{h_0}^2\xi\gamma_{\mathrm{DF}_{\mathrm{su}}} + (1-P_D)\frac{\widetilde{h_0}^2\xi\gamma_{\mathrm{DF}_{\mathrm{su}}}}{1+l_0^{\,2}\gamma_{\mathrm{pu}}}.\end{aligned} \tag{15}$$

The SNR probability density function (PDF) of the direct link for DF strategy is derived in Appendix $Z = X + Y$:

$$f(x) = \frac{\lambda_{h_0^1}\lambda_{h_0^2}}{\lambda_{h_0^2} - \lambda_{h_0^1}}\left(e^{-\lambda_{h_0^1}x} - e^{-\lambda_{h_0^2}x}\right), \tag{16}$$

where $\lambda_{h_0^1} = 1/P_D\xi\gamma_{\mathrm{DF}_{\mathrm{su}}}\Omega_0$ and $\lambda_{h_0^2} = (1+l_0^{\,2}\gamma_{\mathrm{pu}})/(1-P_D)\xi\gamma_{\mathrm{DF}_{\mathrm{su}}}\Omega_0$.

The SNR of SU BS-to-relaying node link for DF strategy is

$$\begin{aligned}\gamma_{b-k} &= E\left\{\mathrm{SNR}_{b-k}\right\}\\ &= P_D\widetilde{h_1^k}^2\xi\gamma_{\mathrm{DF}_{\mathrm{su}}} + (1-P_D)\frac{\widetilde{h_1^k}^2\xi\gamma_{\mathrm{DF}_{\mathrm{su}}}}{1+l_1^{\,2}\gamma_{\mathrm{pu}}}.\end{aligned} \tag{17}$$

The SNR of the relay node-to-SU for DF strategy is

$$\begin{aligned}\gamma_{k-\mathrm{su}} &= E\left\{\mathrm{SNR}_{k-\mathrm{su}}\right\}\\ &= P_D\widetilde{h_2}^2\xi\gamma_{\mathrm{DF}_{\mathrm{su}}}\\ &\quad + (1-P_D)\frac{\widetilde{h_2}^2(1-\xi)\gamma_{\mathrm{DF}_{\mathrm{su}}}}{l_1^{\,2}\widetilde{h_2}^2\gamma_{\mathrm{pu}} + l_0^{\,2}\gamma_{\mathrm{pu}} + 1}.\end{aligned} \tag{18}$$

Then the SNR PDF of the relay node-to-SU link for DF strategy is derived in Appendix $Z = Z_3 + W$:

$$f(x) = \lambda_{h_2^1}\lambda_{h_2^2}\lambda_{h_2^3}e^{\lambda_{h_2^2}\theta}\frac{xe^{-(\lambda_{h_2^3}/2)x}}{\left(\left(\lambda_{h_2^1}/2\right)x + \lambda_{h_2^2}\right)^2}, \tag{19}$$

where $\lambda_{h_2^1} = 1/(1-P_D)(1-\xi)\gamma_{\mathrm{DF}_{\mathrm{su}}}\Omega_2$, $\lambda_{h_2^2} = 1/l_1^{\,2}\gamma_{\mathrm{pu}}\Omega_2$, $\lambda_{h_2^3} = 1/P_D(1-\xi)\gamma_{\mathrm{DF}_{\mathrm{su}}}\Omega_2$, and $\theta = l_0^{\,2}\gamma_{\mathrm{pu}} + 1$. The outage probability of the SU using maximum channel gain for DF strategy is

$$\begin{aligned}P_{\mathrm{out}}^{\mathrm{cg}} &= P_{h_{b-k}^{\max}}P\left\{\widetilde{h_1^{\max}} < \widetilde{h_0}\right\}P\left\{\gamma_{b-\mathrm{su}} < \left(2^{2R_{\mathrm{su}}}-1\right)\right\}\\ &\quad + P_{h_{b-k}^{\max}}P\left\{\widetilde{h_1^{\max}} > \widetilde{h_0}\right\}\\ &\quad \cdot P\left\{\min\left(\gamma_{b-k},\gamma_{k-\mathrm{su}}\right) < \left(2^{2R_{\mathrm{su}}}-1\right)\right\},\end{aligned} \tag{20}$$

and the probability of selecting the maximum channel gain node is

$$\begin{aligned}P_{h_{b-k}^{\max}} &= P\left\{\max\left(\widetilde{h_1^1},\widetilde{h_1^2},\ldots,\widetilde{h_1^N}\right)\right\} = \prod_{k=1}^{N}P_k\left(\widetilde{h_1^k}\right.\\ &\quad \left. < \frac{2^{2R_{\mathrm{su}}}-1}{P_D\xi\gamma_{\mathrm{DF}_{\mathrm{su}}} + (1-P_D)\xi\left(\gamma_{\mathrm{DF}_{\mathrm{su}}}/\left(1+l_0^{\,2}\gamma_{\mathrm{pu}}\right)\right)}\right),\end{aligned} \tag{21}$$

where P_k is the probability of the case when the kth node channel gain is less than the maximum channel gain.

3.1.2. Max Signal-to-Noise Ratio. The SNR PDF of direct link using maximum SNR scheme is the same as (16). The SNR PDF of relay node-to-SU is the same as (19). The SNR PDF of SU BS-to-relay node is

$$f(x) = \frac{\lambda_{h_1^1}\lambda_{h_1^2}}{\lambda_{h_1^2} - \lambda_{h_1^1}}\left(e^{-\lambda_{h_1^1}x} - e^{-\lambda_{h_1^2}x}\right), \tag{22}$$

where $\lambda_{h_1^1} = 1/P_D\xi\gamma_{\mathrm{DF_{su}}}\Omega_1^k$ and $\lambda_{h_1^2} = (1 + {l_1}^2\gamma_{\mathrm{pu}})/(1 - P_D)\xi\gamma_{\mathrm{DF_{su}}}\Omega_1^k$. The outage probability of the SU using maximum SNR for DF strategy is

$$\begin{aligned} P_{\mathrm{out}}^{\mathrm{snr}} &= P_{\gamma_{b-k}^{\max}} P\left\{\gamma_{b-\mathrm{su}}^{\max} > \gamma_{b-k}^{\max}\right\} P\left\{\gamma_{b-\mathrm{su}} < \left(2^{2R_{\mathrm{su}}} - 1\right)\right\} \\ &+ P_{\gamma_{b-k}^{\max}} \left\{P\left\{\gamma_{b-\mathrm{su}}^{\max} < \gamma_{b-k}^{\max}\right\} \right. \\ &\left. \cdot P\left\{\min\left(\gamma_{b-k}, \gamma_{k-\mathrm{su}}\right) < \left(2^{2R_{\mathrm{su}}} - 1\right)\right\}\right\}, \end{aligned} \tag{23}$$

where selecting maximum SNR relay node probability is

$$P_{\gamma_{b-k}^{\max}} = P\left\{\max\left(\gamma_{b-k}^1, \gamma_{b-k}^2, \ldots, \gamma_{b-k}^N\right)\right\}. \tag{24}$$

3.2. Amplify-and-Forward Relaying

3.2.1. Max Channel Gain. The SU SNR of the direct link for AF strategy can be written as

$$\begin{aligned} \gamma_{b-\mathrm{su}} &= E\left\{\mathrm{SNR}_{b-\mathrm{su}}\right\} \\ &= P_D\widetilde{h_0}^2\xi\gamma_{\mathrm{AF_{su}}} + \left(1 - P_D\right)\frac{\widetilde{h_0}^2\xi\gamma_{\mathrm{AF_{su}}}}{1 + {l_0}^2\gamma_{\mathrm{pu}}}, \end{aligned} \tag{25}$$

and the SNR PDF of the direct link for AF strategy is

$$f(x) = \frac{\lambda_{h_0^1}\lambda_{h_0^2}}{\lambda_{h_0^2} - \lambda_{h_0^1}}\left(e^{-\lambda_{h_0^1}x} - e^{-\lambda_{h_0^2}x}\right), \tag{26}$$

where $\lambda_{h_0^1} = 1/P_D\xi\gamma_{\mathrm{AF_{su}}}\Omega_0$ and $\lambda_{h_0^2} = (1 + {l_0}^2\gamma_{\mathrm{pu}})/(1 - P_D)\xi\gamma_{\mathrm{AF_{su}}}\Omega_0$. The SNR of SU BS-to-relay nodes is

$$\begin{aligned} \gamma_{b-k} &= E\left\{\mathrm{SNR}_{b-k}\right\} \\ &= P_D\xi\widetilde{h_1^k}^2\gamma_{\mathrm{AF_{su}}} + \left(1 - P_D\right)\frac{\widetilde{h_1^k}^2\xi\gamma_{\mathrm{AF_{su}}}}{1 + {l_1}^2\gamma_{\mathrm{pu}}}. \end{aligned} \tag{27}$$

The SNR of the selected relay node-to-SU is

$$\begin{aligned} \gamma_{k-\mathrm{su}} &= E\left\{\mathrm{SNR}_{k-\mathrm{su}}\right\} \\ &= P_D\alpha^2\widetilde{h_2}^2\left(1 - \xi\right)\gamma_{\mathrm{AF_{su}}} \\ &+ \left(1 - P_D\right)\frac{\alpha^2\widetilde{h_2}^2\left(1 - \xi\right)\gamma_{\mathrm{AF_{su}}}}{\alpha^2{l_1}^2\widetilde{h_2}^2\gamma_{\mathrm{pu}} + {l_0}^2\alpha^2\gamma_{\mathrm{pu}} + 1}. \end{aligned} \tag{28}$$

Then the SNR PDF of the selected relay node-to-SU is

$$f(x) = \lambda_{h_2^1}\lambda_{h_2^2}\lambda_{h_2^3}e^{\lambda_{h_2^2}\theta}\frac{xe^{-(\lambda_{h_2^3}/2)x}}{\left(\left(\lambda_{h_2^1}/2\right)x + \lambda_{h_2^2}\right)^2}, \tag{29}$$

where $\lambda_{h_2^1} = 1/(1 - P_D)(1 - \xi)\gamma_{\mathrm{AF_{su}}}\Omega_2$, $\lambda_{h_2^2} = 1/{l_1}^2\gamma_{\mathrm{pu}}\Omega_2$, $\lambda_{h_2^3} = 1/P_D(1 - \xi)\gamma_{\mathrm{AF_{su}}}\Omega_2$, and $\theta = {l_0}^2\gamma_{\mathrm{pu}} + 1$. The outage probability of the SU using maximum channel gain for AF strategy is the same as (20); the probability of selecting the maximum channel gain relay node is

$$\begin{aligned} P_{h_{b-k}^{\max}} &= P\left\{\max\left(\widetilde{h_1^1}, \widetilde{h_1^2}, \ldots, \widetilde{h_1^N}\right)\right\} = \prod_{k=1}^{N} P_k\left(\widetilde{h_1^k}\right. \\ &\left. < \frac{2^{2R_{\mathrm{su}}} - 1}{P_D\xi\gamma_{\mathrm{AF_{su}}} + \left(1 - P_D\right)\xi\left(\gamma_{\mathrm{AF_{su}}}/\left(1 + {l_0}^2\gamma_{\mathrm{pu}}\right)\right)}\right). \end{aligned} \tag{30}$$

3.2.2. Max Signal-to-Noise Ratio. The SNR PDF of direct link using max SNR scheme is the same as (26). The SNR PDF of the selected node-to-SU using max SNR scheme is the same as (29). The SNR PDF of SU BS-to-relay nodes using max SNR scheme is

$$f(x) = \frac{\lambda_{h_1^1}\lambda_{h_1^2}}{\lambda_{h_1^2} - \lambda_{h_1^1}}\left(e^{-\lambda_{h_1^1}x} - e^{-\lambda_{h_1^2}x}\right), \tag{31}$$

where $\lambda_{h_1^1} = 1/P_D\xi\gamma_{\mathrm{AF_{su}}}\Omega_1^k$ and $\lambda_{h_1^2} = (1 + {l_1}^2\gamma_{\mathrm{pu}})/(1 - P_D)\xi\gamma_{\mathrm{AF_{su}}}\Omega_1^k$. The outage probability of the SU using maximum SNR for AF strategy is the same as (23).

4. Simulation and Performance Analysis

In this section, the numerical simulations are performed using the analysis of outage probability which is obtained in the previous section. We assume that $R_{\mathrm{pu}} = 1$ bps/Hz and relay nodes $N = 8$, the average channel gain value is $1/d^{\varepsilon}$, where d is the channel distance of each link, and ε is pass loss exponent ($\varepsilon = 2$ assumed). We also assume that $d_{f0} = 2.5$, $d_{f1} = 1.5$, $d_{g0} = 1$, $d_{f0} = 2.5$, $d_{f1} = 1.5$, $d_{h0} = 2.5$, $d_{h1} = 1.5$, $d_{h2} = 1$, $d_{l0} = 2.5$, and $d_{l1} = 1.5$. For all the simulations, we make the assumption that the distributions of the noise parts of the received PU or SU signals are Gaussian.

Figure 2 shows the SU outage probability versus power allocation factor ξ with different values of PU SNR when the detection probability is set to 0.9. One sees that the SU outage probability decreases when PU SNR increases and the power allocation factor increases.

Figure 3 shows the SU outage probability versus detection probability P_D and SU BS power allocation factor ξ when PU SNR is set to 20 dB. One sees that the SU outage probability decreases when the detection probability increases and SU BS power allocation factor increases.

Figure 4 shows the SU outage probability versus power allocation factor ξ with different values of PU SNR when the detection probability is set to 0.9. One observes that the SU outage probability decreases when PU SNR increases and the detection probability increases. Compared with Figure 2, the performance of using maximum channel gain is better than using maximum SNR when the SU BS power allocation factor $\xi \sim [0\text{–}0.1]$, while it is worse when the SU BS power allocation factor $\xi \sim [0.1\text{–}1]$.

Figure 5 shows the SU outage probability versus detection probability P_D and power allocation factor ξ when the PU SNR is set to 20 dB. One sees that the SU outage probability decreases when the detection probability increases and SU BS

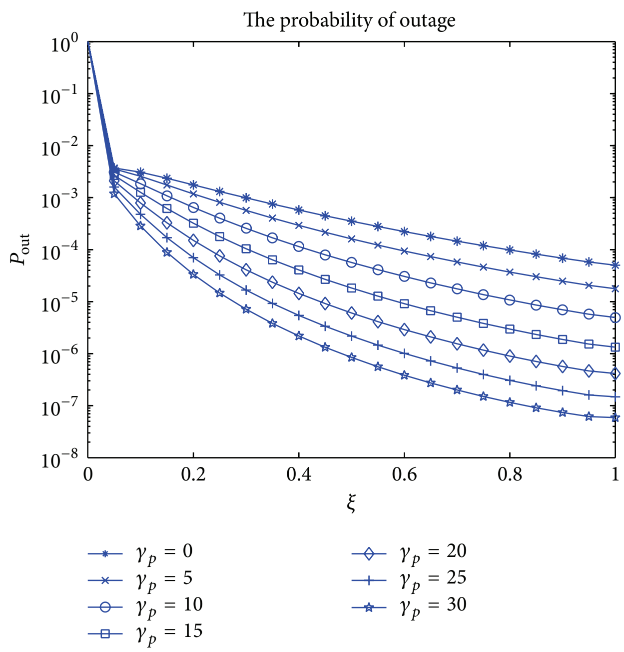

FIGURE 2: Max channel gain node with different ξ and γ_p using DF.

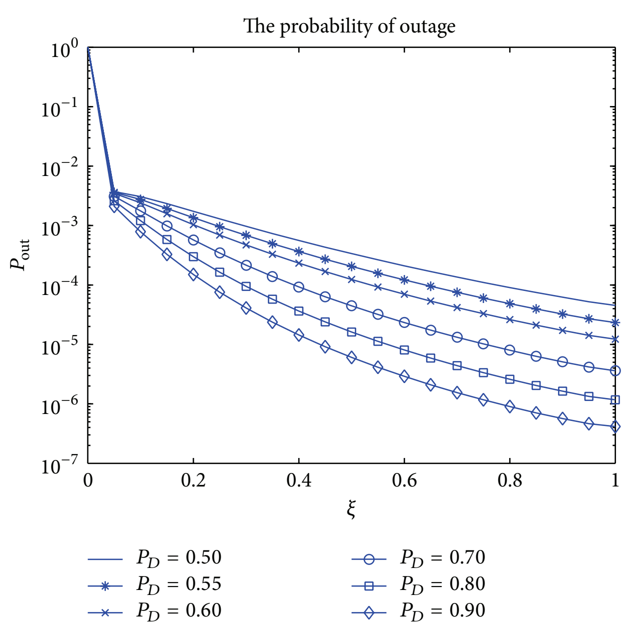

FIGURE 3: Max channel gain node with different ξ and P_D using DF.

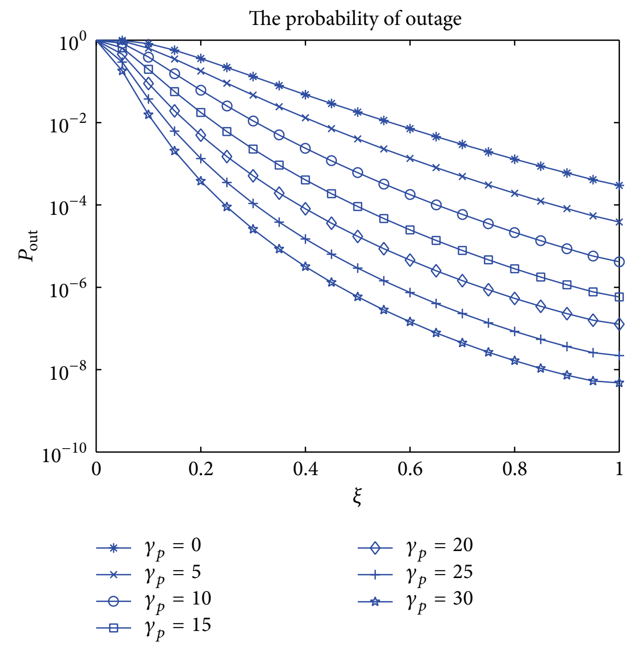

FIGURE 4: Max SNR with different ξ and γ_p using DF.

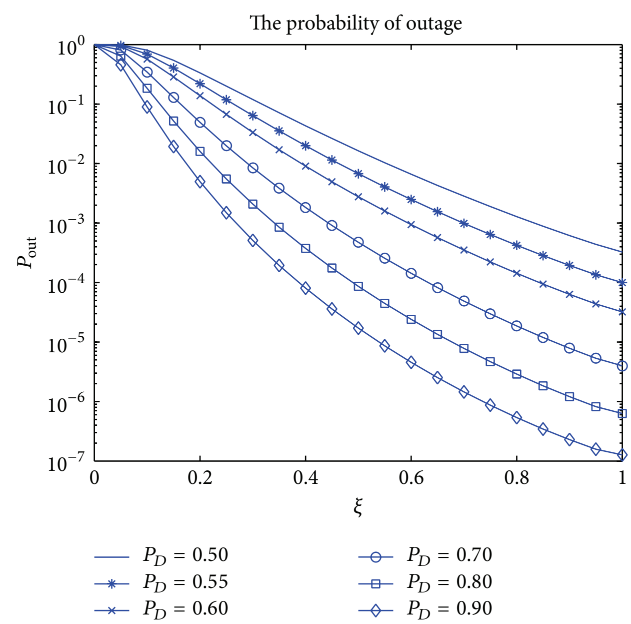

FIGURE 5: Max SNR with different ξ and P_D using DF.

power allocation factor increases. Compared with Figure 3, the performance of using maximum channel gain is better than using maximum SNR when the detection probability $P_D < 0.60$, while it is worse when the detection probability $P_D > 0.60$. The performance of using maximum channel gain is better than using maximum SNR when the SU BS power allocation factor $\xi \sim [0\text{–}0.1]$, while it is worse when the SU BS power allocation factor $\xi \sim [0.1\text{–}1]$.

Figure 6 shows the SU outage probability versus power allocation factor ξ with different values of PU SNR when the detection probability is set to 0.9. When SNR $\leq$ 10 dB, the SU outage probability decreases while the BS power allocation factor increases. When the SU power allocation factor $\xi \sim [0\text{–}0.55]$ the SU outage probability decreases. The SU outage probability increases when the SU power allocation factor $\xi \sim [0.55\text{–}0.1]$ and PU SNR is 30 dB. On the other hand, the larger the PU SNR is the smaller the SU BS power allocation factor corresponding to the minimum outage probability will be.

Figure 7 shows the SU outage probability versus detection probability P_D and power allocation factor ξ when

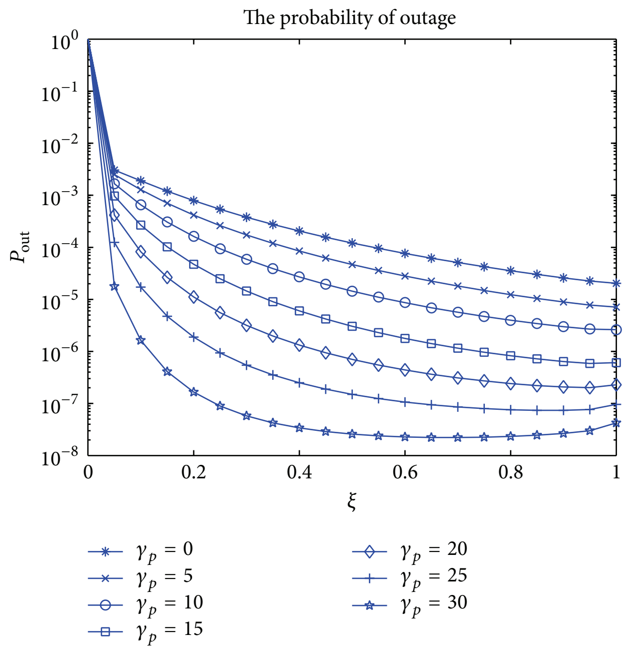

Figure 6: Max channel gain node with different ξ and γ_p using AF.

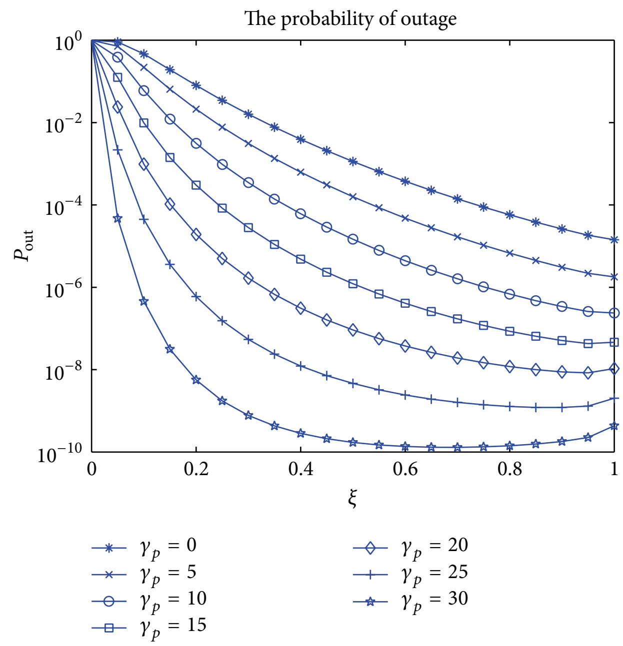

Figure 8: Max SNR with different ξ and γ_p using AF.

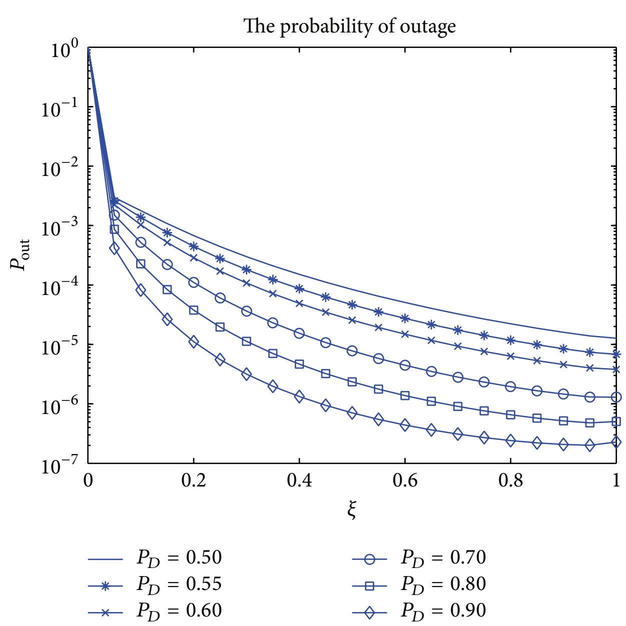

Figure 7: Max channel gain node with different ξ and P_D using AF.

the PU SNR is 20 dB. In Figure 7, one sees that the SU outage probability decreases when the detection probability increases; one also observes that the SU outage probability can reach an error floor when the SU BS power allocation factor changes with different detection probability. Moreover, the larger the detection probability is, the smaller the SU BS power allocation factor corresponding to the minimum outage probability will be.

Figure 8 shows the SU outage probability versus power allocation factor ξ with different values of PU SNR when the detection probability is set to 0.9. One observes that the SU outage probability decreases when the BS power allocation factor increases and the SU power allocation factor $\xi \sim [0–0.55]$, while the SU outage probability increases when the SU power allocation factor $\xi \sim [0.55–0.1]$ and PU SNR is 30 dB. On the other hand, the larger the PU SNR is, the smaller the SU BS power allocation factor corresponding to the minimum outage probability will be. Compared with Figure 6, the performance of using maximum channel gain is better than using maximum SNR when the SU BS power allocation factor $\xi \sim [0–0.1]$, while it is worse when the SU BS power allocation factor $\xi \sim [0.1–1]$.

Figure 9 shows the SU outage probability versus detection probability P_D and power allocation factor ξ when the PU SNR is set to 20 dB. One observes that SU outage probability can reach an error floor when the SU BS power allocation factor changes with different detection probability. What is more, the larger the detection probability is, the smaller the SU BS power allocation factor corresponding to the minimum outage probability will be. Otherwise, compared with Figure 7, the performance of using maximum channel gain is better than that using maximum SNR when the detection probability $P_D < 0.60$, while it is worse when the detection probability $P_D > 0.60$. The performance of using maximum channel gain is better than using maximum SNR when the SU BS power allocation factor $\xi \sim [0–0.1]$, while it is worse when the SU BS power allocation factor $\xi \sim [0.1–1]$.

Figure 10 shows the SU outage probability versus detection probability P_D, maximum channel gain, maximum SNR, and power allocation factor ξ when the PU SNR is set to 20 dB. When $P_D = 0.7$, the outage probability of maximum channel gain is better than maximum SNR while $\xi < 0.75$; when $P_D = 0.8$, the outage probability of maximum channel gain is better than maximum SNR in the case of $\xi < 0.45$;

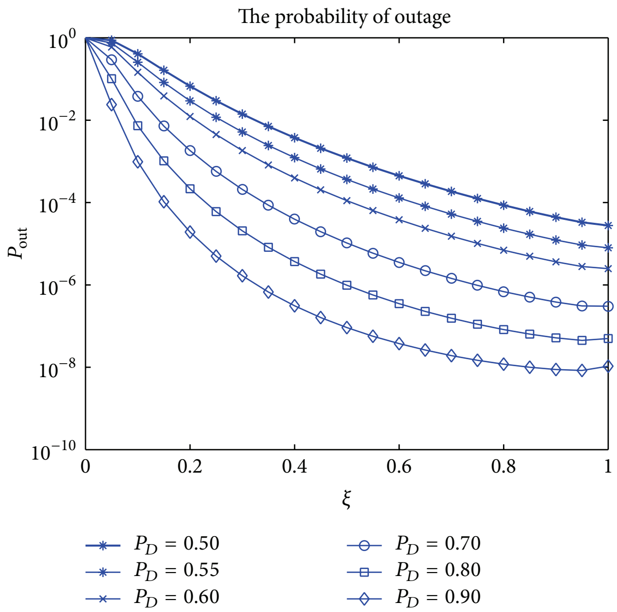

Figure 9: Max SNR with different ξ and P_D using AF.

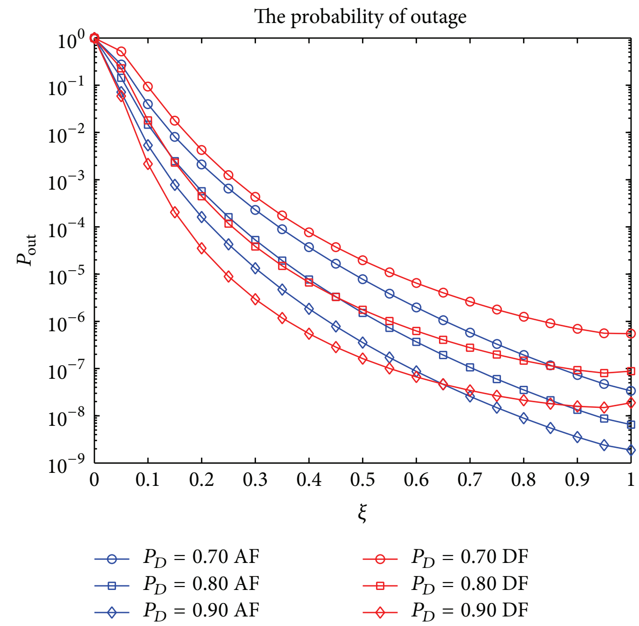

Figure 11: AF and DF ξ and P_D using max SNR.

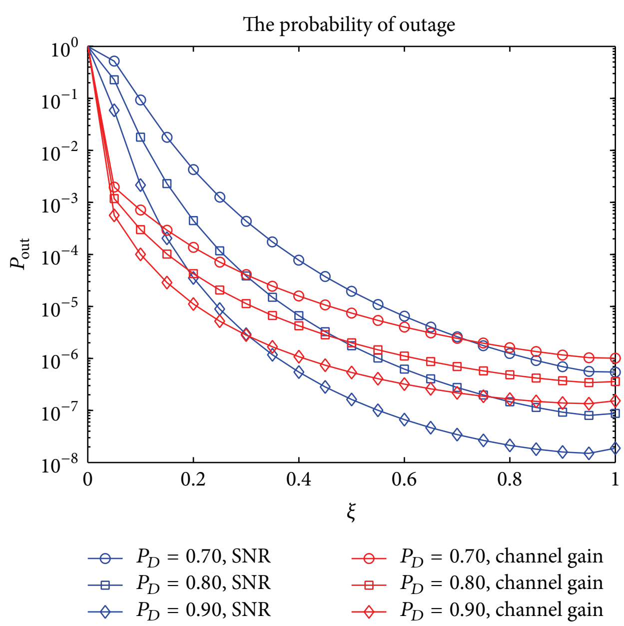

Figure 10: Max SNR and channel gain with different ξ and P_D using AF.

when $P_D = 0.9$, the outage probability of maximum channel gain is better than maximum SNR while $\xi < 0.30$. When $P_D = 0.70$, the outage probability is intersected at $\xi = 0.75$; when $P_D = 0.8$, the outage probability is intersected at $\xi = 0.45$; when $P_D = 0.9$, the outage probability is intersected at $\xi = 0.30$. So maximum channel gain is better than maximum SNR when the SU BS power allocation factor is small; on the contrary, it is worse when the SU BS power allocation factor is big.

Figure 11 shows the SU outage probability versus detection probability PD, AF, DF, and power allocation factor ξ when the PU SNR is set to 20 dB. When $P_D = 0.7$, the outage probability of AF is better than DF; when $P_D = 0.8$, the outage probability of AF is nearly equal to DF in the case of $\xi < 0.50$ and the outage probability of AF is better than DF while $\xi > 0.50$; when $P_D = 0.9$, the outage probability of AF is better than DF in the case of $\xi < 0.65$. Therefore only when the SU BS power allocation factor is small and detection probability is big can DF be better than AF; in contrast it is different.

5. Conclusions

In DF relaying, the outage probability decreases when the power allocation factor increases. While in AF relaying, the outage probability can reach a minimum value under the right power allocation factor and the right detection probability. In addition, the larger the PU SNR and detection probability are, the smaller the SU base station power allocation factor corresponding to the minimum outage probability that will be required is. The larger the detection probability is, the smaller the SU base station power allocation factor corresponding to the outage probability minimum value that will be required is. Moreover, the relaying scheme based on the maximum channel gain has the better performance based on the maximum SNR when the power allocation factor and detection probability are small, while the relaying scheme based on the maximum SNR has the better performance based on the maximum channel gain when the power allocation factor is large. Compared with DF relaying, AF relaying amplifies the transmitting signal; therefore, what is more, only when the SU BS power allocation factor is small and detection probability is big can the outage performance of DF be better than AF; otherwise the outage performance of AF is better than DF.

Appendix

For the exponential distribution, if $X \sim E(\lambda_1)$, $Y \sim E(\lambda_2)$, $W \sim E(\lambda_3)$.

Consider $Z_1 = X + Y$:

$$\begin{aligned} f_1(z) &= \int_0^z \lambda_1 e^{-\lambda_1(z-x)} \lambda_2 e^{-\lambda_2 x} dx \\ &= \lambda_1 \lambda_2 e^{-\lambda_1 z} \int_0^z e^{-(\lambda_2-\lambda_1)x} dx \\ &= \frac{\lambda_1\lambda_2}{\lambda_2-\lambda_1} e^{-\lambda_1 z}\left(1-e^{-(\lambda_2-\lambda_1)z}\right) \\ &= \frac{\lambda_1\lambda_2}{\lambda_2-\lambda_1}\left(e^{-\lambda_1 z}-e^{-\lambda_2 z}\right). \end{aligned} \tag{A.1}$$

Consider $Z_2 = Y + \theta$:

$$f_2(z) = \lambda_2 e^{-\lambda_2(z-\theta)} = \lambda_2 e^{\lambda_2\theta} e^{-\lambda_2 z}. \tag{A.2}$$

Consider $Z_3 = X/Z_2$:

$$\begin{aligned} f_3(z) &= \int_0^\infty x f(xz) f(x)\, dx \\ &= e^{\lambda_2\theta} \int_0^\infty x\lambda_1 e^{-\lambda_1 xz} \lambda_2 e^{-\lambda_2 x} dx \\ &= \frac{\lambda_1\lambda_2 e^{\lambda_2\theta}}{(\lambda_1 z+\lambda_2)^2}. \end{aligned} \tag{A.3}$$

Consider $Z = Z_3 + W$:

$$\begin{aligned} f(z) &= \int_0^z f(z-x) f(x)\, dx \\ &= \int_0^z \frac{\lambda_1\lambda_2 e^{\lambda_2\theta}}{(\lambda_1 x+\lambda_2)^2} \lambda_3 e^{-\lambda_3(z-x)} dx \\ &= \lambda_1\lambda_2\lambda_3 e^{\lambda_2\theta} e^{-\lambda_3 z} \int_0^z \frac{e^{\lambda_3 x}}{(\lambda_1 x+\lambda_2)^2} dx \\ &= \lambda_2\lambda_3 e^{\lambda_2\theta} e^{-\lambda_3\lambda_2/\lambda_1} e^{-\lambda_3 z} \int_{\lambda_2}^{z\lambda_1+\lambda_2} \frac{e^{(\lambda_3/\lambda_1)x}}{x^2} dx \\ &= \lambda_2\lambda_3 e^{\lambda_2\theta} e^{-(\lambda_3\lambda_2/\lambda_1)} e^{-\lambda_3 z} \frac{e^{(\lambda_3/\lambda_1)\zeta}}{\zeta^2} z\lambda_1; \\ &\qquad\qquad \lambda_2 < \zeta < z\lambda_1 + \lambda_2 \\ &\approx \lambda_2\lambda_3 e^{\lambda_2\theta} e^{-\lambda_3\lambda_2/\lambda_1} e^{-\lambda_3 z} \frac{e^{(\lambda_3/\lambda_1)(z\lambda_1/2+\lambda_2)}}{((\lambda_1/2)z+\lambda_2)^2} z\lambda_1 \\ &= \lambda_1\lambda_2\lambda_3 e^{\lambda_2\theta} \frac{z e^{-(\lambda_3/2)z}}{((\lambda_1/2)z+\lambda_2)^2}. \end{aligned} \tag{A.4}$$

Competing Interests

The authors declare that they have no competing interests.

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