PERFORMANCE ANALYSIS OF BEST RELAY SELECTION STRATEGY BASED ON POTENTIAL RELAY IN UNDERLAY COGNITIVE NETWORKS

Suoping LI[1]*,Yang LIU[1], Xiaokai CHANG[1], Nana YANG[1]

In underlay cognitive radio networks (CRNs), best relay selection strategy (BRSS) has received widespread attention in recent years as an effective relay selection strategy. The implementation of BRSS depends on a large amount of channel state information (CSI), which increases the energy consumption of secondary networks (SNs). This paper introduces an improved best relay selection strategy (IBRSS) based on potential relay that reduces demand on CSI, and at the same time improve performance of SNs. This paper proposes a system model of mutual interference between SNs and primary networks (PNs). By deriving signal-to-interference and noise ratio (SINR), it is proved that the IBRSS can reduce outage probability (OP) and bit error rate (BER) of SNs.

Keywords: cognitive radio; best relay selection strategy; outage probability; bit error rate; cooperative relay transmission

1. Introduction

With the massive growth of new generation wireless devices, the demand for spectrum progressively increases. Therefore, the need to improve spectrum efficiency has become critical. In recent years, improving spectrum efficiency using cognitive radio (CR) [1-3] technology has received widespread attention.

In underlay spectrum access mode [4-6], primary networks (PNs) and secondary networks (SNs) share the same channel, but SNs must meet strict interference constraints, thus resulting in the reduction of the transmission range and the deterioration of the quality of service (QoS) of SNs. To solve the above problems, many scholars have carried out many studies. In [7], the authors proved that cooperative relay transmission could expand the transmission range and improve QoS without increasing power. In [8], the authors claimed that the cooperative relay transmission has a broad prospect in CR.

The concept of the best relay selection strategy (BRSS) was reported [9]. This strategy selects the relay that can provide the largest signal-to-noise ratio (SNR) for data forwarding. Moreover, the authors in [10], expressed that although BRSS has many advantages, it cannot be applied to CR directly. They proposed a

[1] Department of Applied Mathematics, School of Science, Lanzhou University of Technology, China, corresponding author's e-mail: lsuop@163.com

new relay selection strategy that considers SNR and interference when selecting forward relay (FR). However, the authors only paid attention to the interference caused by the SNs to the PNs, and that caused by the PNs to the SNs was not considered. The anti-interference technologies that can be used in CR, including spectrum shaping, predistortion filtering and spread spectrum were proposed in [11-13]. However, a relay is generally considered as a simple node, which cannot be equipped with complex anti-interference technology. So, the interference of the PNs to the relays cannot be ignored. Attention has been paid to interference of PNs to relays, and the analysed of BRSS's performance in [14], but the BRSS implementation demands much of CSI. In the actual communication, obtaining CSI is difficult.

In [10, 14], amplify-and-forward (AF) was used to transmit data in relays. This method is simple to implement and can reduce BER and outage probability (OP). Therefore, we adopt the forwarding technology based on AF.

The main contributions of this paper are as follows:

- This paper builds a system model of PNs and SNs mutual interference, and the channel gains are modelled as an independent differently distribution random variable. The cumulative distribution function (CDF) of SINR is derived, and the OP and BER are calculated.
- It introduces IBRSS that reduces the demand for CSI and improves the performance of SNs.
- The mutual interference between PNs and SNs is studied. The changes of SNs performance in mutual interference scene are revealed.

2. System model and SINR analysis

2.1 System models and assumptions

Fig. 1 presents the system model of the IBRSS that consists of a secondary source node S, a secondary destination node D, L relay nodes $R_i, i = 1,2,3\ldots L$, a primary source node P and a primary destination node Q.

The assumptions of system model are as follows:

- The nodes S and Q cannot communicate directly;
- In this paper, the Rayleigh fading channel model is used, and the channel coefficient of link $A \rightarrow B$ is denoted by $h_A^B, A, B \in \{S, D, P, Q, R_1, R_2, \ldots R_L\}$. In addition, $h_A^B = h_B^A$;
- All noises are additive white gaussian noise (AWGN), with an average value of 0 and a power spectral density of 1;

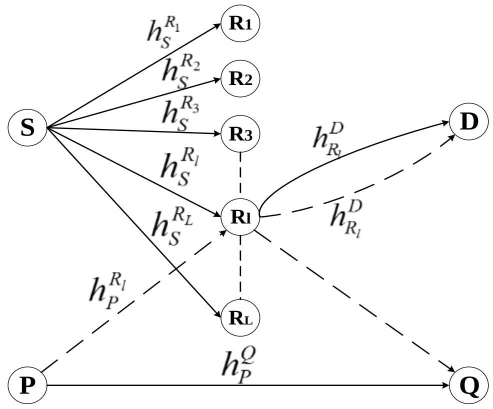

Fig. 1. System transmission model of the IBRSS
(— represents transmission link, —— represents interference link)

2.2 Analysis of secondary networks SINR

To get the form of SINR, we first analyze the SNs signal. At the end of the first time slot, the signal received by relay R_l is as follows:

$$y_{R_l} = \sqrt{P_s} h_S^{R_l} x + n_0 + \sqrt{P_P} h_P^{R_l} x' \tag{1}$$

where P_S and P_P are the transmission powers of S and P, respectively. x and x' are the signals sent by S and P, respectively. n_0 is the channel noise.

Since the relay uses AF to forward data, the signal received by D is:

$$y_D = G y_{R_l} h_{R_l}^D + n_0 + \sqrt{P_P} h_P^D x' \tag{2}$$

where G represents the amplification factor.

Substituting (1) into (2), we get:

$$y_D = G\sqrt{P_S} h_S^{R_l} h_{R_l}^D x + G h_{R_l}^D n_0 + G\sqrt{P_P} h_P^{R_l} h_{R_l}^D x' + n_0 + \sqrt{P_P} h_P^D x' \tag{3}$$

The signal received by node Q is:

$$y_Q = \sqrt{P_P} h_P^Q x' + n_0 + \sqrt{P_S} h_S^Q x + G y_{R_l} h_{R_l}^Q \tag{4}$$

Substituting (1) into (4), we get:

$$y_Q = \sqrt{P_P} h_P^Q x' + n_0 + \sqrt{P_S} h_S^Q x + G\sqrt{P_S} h_S^{R_l} h_{R_l}^Q x + G h_{R_l}^Q n_0 + G\sqrt{P_P} h_P^{R_l} h_{R_l}^Q x' \tag{5}$$

A simple transformation of (5) gives:

$$y_Q = \left(\sqrt{P_P} h_P^Q + G\sqrt{P_P} h_P^{R_l} h_{R_l}^Q\right) x' + \left(\sqrt{P_S} h_S^Q + G\sqrt{P_S} h_S^{R_l} h_{R_l}^Q\right) x + \left(G h_{R_l}^Q + 1\right) n_0 \tag{6}$$

Based on the above results, we will now derive SINR.

Because the relay uses AF, the relationship between P_S and P_{R_l} is as follows:

$$P_{R_l} = G^2 (P_S |h_S^{R_l}|^2 + P_P |h_P^{R_l}|^2 + 1) \tag{7}$$

$$G^2 = \frac{P_{R_l}}{P_S |h_S^{R_l}|^2 + P_P |h_P^{R_l}|^2 + 1} \tag{8}$$

where P_{R_l} is transmission power of R_l, G^2 is amplification gain.

According to (3), the SINR of link $S \to R_l \to D$ is:

$$\eta_S^D = \frac{G^2 P_S |h_S^{R_l}|^2 |h_{R_l}^D|^2}{G^2 |h_{R_l}^D|^2 + G^2 P_P |h_P^{R_l}|^2 |h_{R_l}^D|^2 + 1 + P_P |h_P^D|^2} \tag{9}$$

Substituting (8) into (9), we get:

$$\eta_S^D = \frac{\dfrac{P_S P_{R_l} |h_S^{R_l}|^2 |h_{R_l}^D|^2}{P_S |h_S^{R_l}|^2 + P_P |h_P^{R_l}|^2 + 1}}{\dfrac{P_{R_l} |h_{R_l}^D|^2}{P_S |h_S^{R_l}|^2 + P_P |h_P^{R_l}|^2 + 1} + \dfrac{P_{R_l} P_P |h_P^{R_l}|^2 |h_{R_l}^D|^2}{P_S |h_S^{R_l}|^2 + P_P |h_P^{R_l}|^2 + 1} + 1 + P_P |h_P^D|^2} \tag{10}$$

After simplifying (10), it holds that:

$$\eta_S^D = \frac{P_{R_l} \gamma_S^{R_l} |h_{R_l}^D|^2}{P_{R_l} |h_{R_l}^D|^2 + P_{R_l} I_P^{R_l} |h_{R_l}^D|^2 + \gamma_S^{R_l} + I_P^{R_l} + 1} = \frac{\gamma_S^{R_l} \gamma_{R_l}^D}{\gamma_{R_l}^D + \gamma_{R_l}^D I_P^{R_l} + \gamma_S^{R_l} + I_P^{R_l} + 1 + \gamma_S^{R_l} I_P^D + I_P^D I_P^{R_l} + I_P^D} \tag{11}$$

where $\gamma_S^{R_l} = P_S |h_S^{R_l}|^2$, $\gamma_{R_l}^D = P_{R_l} |h_{R_l}^D|^2$, $I_P^{R_l} = P_P |h_P^{R_l}|^2$, $I_P^D = P_P |h_P^D|^2$. $\gamma_S^{R_l}$ and $\gamma_{R_l}^D$ are SNR of the links $S \to R_l$ and $R_l \to D$, respectively. $I_P^{R_l}$ and I_P^D are interferences of the links $P \to R_l$ and $P \to D$, respectively. According to the previous assumption, $I_P^D = 0$. Simplify (11) to get:

$$\eta_S^D = \frac{\gamma_S^{R_l} \gamma_{R_l}^D}{\gamma_{R_l}^D + \gamma_S^{R_l} + I_P^{R_l} + \gamma_{R_l}^D I_P^{R_l} + 1} = \frac{\dfrac{\gamma_S^{R_l}}{I_P^{R_l} + 1} \cdot \gamma_{R_l}^D}{\gamma_{R_l}^D + 1 + \dfrac{\gamma_S^{R_l}}{I_P^{R_l} + 1}}$$

Observing the above formula, we find out that η_S^D is very complicated. $\dfrac{\gamma_S^{R_l}}{I_P^{R_l} + 1}$ is SINR of the link $S \to R_l$. $\gamma_{R_l}^D$ is SINR of the link $R_l \to D$. ($\gamma_{R_l}^D$ is also SNR, because there does not exist interfere in link $R_l \to D$).

According to [15], we have the following approximation:

$$\eta_S^D \approx \min \left\{ \frac{\gamma_S^{R_l}}{I_P^{R_l} + 1}, \gamma_{R_l}^D \right\} \tag{12}$$

Next, we will derive CDF of η_S^D.

Proposition 1: Assume $X=\gamma_S^{R_l}$, $Y=I_P^{R_l}$ and $U=\gamma_{R_l}^D$ follow the exponential distribution with parameters λ_l, β_l and α_l, where $\lambda_l=\frac{1}{\hat{\gamma}_S^{R_l}}$, $\beta_l=\frac{1}{\hat{I}_P^{R_l}}$ and $\alpha_l=\frac{1}{\hat{\gamma}_{R_l}^D}$. Then, the CDF of $V=\eta_S^D$ is:

$$F_V(v)=1-(1-F_Z(v))(1-F_U(v))=1-\left(\frac{\beta_l}{\lambda_l v+\beta_l}e^{-\lambda_l v}\right)\cdot\left(e^{-\alpha_l v}\right) \tag{13}$$

<u>**Proof:**</u> Assume $W=Y+1$, then $F_W(w)=\Pr(Y+1\le w)=\Pr(Y\le w-1)$

When $0\le w\le 1$, $\because Y=I_P^{R_l}>0$, $\therefore F_W(w)=\Pr(Y\le w-1)=0$, $f_W(w)=0$.

When $w>1$, $F_W(w)=\Pr(Y\le w-1)=F_Y(w-1)=1-e^{-\beta_l(w-1)}$, $f_W(w)=\beta_l e^{-\beta_l(w-1)}$.

Assume $Z=\frac{X}{W}=\frac{\gamma_s^{R_l}}{I_P^{R_l}+1}$, then: $F_Z(z)=\Pr(Z\le z)=\Pr\left(\frac{X}{W}\le z\right)=\int_0^\infty \Pr(X\le wz|w)f_W(w)dw$

$$=\int_1^\infty\left(1-e^{-\lambda_l wz}\right)\left(\beta_l e^{-\beta_l(w-1)}\right)dw=1-\left(\frac{\beta_l}{\lambda_l z+\beta_l}\right)e^{-\lambda_l z}$$

Assume $V=\eta_S^D=\min\{Z,U\}$, then:

$$F_V(v)=\Pr(V\le v)=\Pr(\min(Z,U)\le v)=1-\Pr(Z>v)\cdot\Pr(U>v)=1-(1-F_Z(v))\cdot(1-F_U(v))$$

Substituting $F_Z(v)=1-\left(\frac{\beta_l}{\lambda_l v+\beta_l}\right)e^{-\lambda_l v}, F_U(v)=1-e^{-\alpha_l v}$ into the above formula, we get: $F_V(v)=1-(1-F_Z(v))(1-F_U(v))=1-\left(\frac{\beta_l}{\lambda_l v+\beta_l}e^{-\lambda_l v}\right)\left(e^{-\alpha_l v}\right)$.

3. Improved best relay selection strategy（IBRSS）

We denote the interference of the link $x\to Q$ ($x\in\{R_1,R_2,\cdots R_L\}$) by I_x^Q, and I_{th} is the maximum interference threshold set by PNs to meet its own transmission quality. We assume that the selected potential relay aggregation $\Psi=\{R_{i_1},R_{i_2},\cdots,R_{i_M}\}$, where $1\le M\le L, M\in N$. Any relay R_{i_j} in Ψ satisfies $I_{R_{i_j}}^Q=P_{R_{i_j}}\left|h_{R_{i_j}}^Q\right|^2\le I_{th}$.

$H=I_{R_l}^Q$ follows an exponential distribution with parameter ω_l, where $\omega_l=\frac{1}{\hat{I}_{R_l}^Q}$. Probability that relay R_l meets the interference constraint is:

$$\Pr\left(I_{R_l}^Q \le I_{th}\right) = F_{I_{R_l}^Q}\left(I_{th}\right) = 1 - e^{-\omega_l I_{th}} \tag{14}$$

The aggregation of all relays is $\Phi = \{R_1, R_2 ... R_L\}$. The aggregation of potential relays is $\Psi = \{R_{i_1}, R_{i_2}, \cdots, R_{i_M}\}$ and aggregation of non-potential relays is $\Phi - \Psi = \{R_{s_1}, R_{s_2}, \cdots R_{s_N}\}$, $M + N = L$. Let's define the aggregation $\Phi' = \{1, 2...L\}$ and $\Psi' = \{i_1, i_2, \cdots, i_M\}$. There are M elements in Ψ with its probability:

$$P_\Psi = \sum_{M=1}^{L} C_L^M \left(\prod_{i_m \in \Psi'} F_{I_{R_{i_m}}^Q}\left(I_{th}\right)\right) \cdot \left(\prod_{s_n \in \Phi' - \Psi'} \left(1 - F_{I_{R_{s_n}}^Q}\left(I_{th}\right)\right)\right)$$

By substituting (14) into the above formula, we get:

$$P_\Psi = \sum_{M=1}^{L} C_L^M \prod_{i_m \in \Psi'} \left(1 - e^{-\omega_{i_m} I_{th}}\right) \prod_{s_n \in \Phi' - \Psi'} e^{-\omega_{s_n} I_{th}} \tag{15}$$

The SINR of the best relay is expressed as $\eta_{R_{i_l}}^* = \arg\max_{R_{i_l} \in \Psi} \{\eta_S^D\}$. By substituting (12) into the above formula, the $\eta_{R_{i_l}}^*$ is as follows:

$$\eta_{R_{i_l}}^* = \arg\max_{R_{i_l} \in \Psi} \left\{ \min\left\{ \frac{\gamma_S^{R_{i_l}}}{I_P^{R_{i_l}} + 1}, \gamma_{R_{i_l}}^D \right\} \right\} \tag{16}$$

The CDF of $\eta_{R_{i_l}}^*$ is as follows:

$$F_{\eta_{R_{i_l}}^*}(x) = P_\Psi \cdot \Pr\left(\eta_{R_{i_l}}^* < x \middle| \Psi\right) = P_\Psi \cdot \prod_{R_{i_l} \in \Psi} \left[\Pr\left(\min\left\{ \frac{\gamma_S^{R_{i_l}}}{I_P^{R_{i_l}} + 1}, \gamma_{R_{i_l}}^D \right\} < x \right) \right] \tag{17}$$

By substituting (13), (15) into (17), the CDF of $\eta_{R_{i_l}}^*$ is obtained as follows:

$$F_{\eta_{R_{i_l}}^*}(x) = \left(\sum_{M=1}^{L} C_L^M \prod_{i_m \in \Psi'} \left(1 - e^{-\omega_{i_m} I_{th}}\right) \prod_{S_n \in \Phi' - \Psi'} \left(e^{-\omega_{s_n} I_{th}}\right) \right) \left(\prod_{i_m \in \Psi'} \left[1 - \left(\frac{\beta_{i_m}}{\lambda_{i_m} x + \beta_{i_m}} e^{-\lambda_{i_m} x} \right) \cdot \left(e^{-\alpha_{i_m} x} \right) \right] \right) \tag{18}$$

4. Performance analysis

4.1 Outage Probability (OP)

When the link capacity cannot meet the required transmission rate, outage event will occur. We suppose that the required transmission rate of links $S \to R_{i_l} \to D$ and $P \to Q$ is R_{th}. The OP of the link $S \to R_{i_l} \to D$ as follows:

$$P_{out} = \Pr\left(\frac{1}{2}\log_2\left(1 + \eta_{R_{i_l}}^*\right) \le R_{th}\right) = \Pr\left(\log_2\left(1 + \eta_{R_{i_l}}^*\right) \le 2R_{th}\right) = \Pr\left(\eta_{R_{i_l}}^* \le 2^{2R_{th}} - 1\right) = F_{\eta_{R_{i_l}}^*}\left(2^{2R_{th}} - 1\right)$$

Substitute $x = 2^{2R_{th}} - 1$ into (18), the OP of SNs is obtained as follows:

$$P_{out} = \left(\sum_{M=1}^{L} C_L^M \prod_{i_m \in \Psi'} \left(1 - e^{-\omega_{i_m} I_{th}}\right) \prod_{s_n \in \Phi' - \Psi'} \left(e^{-\omega_{s_n} I_{th}}\right) \right) \cdot \prod_{i_m \in \Psi'} \left(1 - \left(\frac{\beta_{i_m} \left(e^{\left(-\lambda_{i_m} - \alpha_{i_m}\right) \cdot \left(2^{2R_{th}} - 1\right)} \right)}{\lambda_{i_m} \cdot 2^{2R_{th}} - \lambda_{i_m} + \beta_{i_m}} \right) \right) \tag{19}$$

4.2 Bit Error Rate

According to [16], the BER of AF can be transformed into the expected form of SINR. So, BER of the link $S \to R_{i_l} \to D$ is obtained as follows:

$${}_S^D P_e = \int_0^\infty \frac{1}{\sqrt{2\pi}} e^{-\frac{x^2}{2}} \cdot F_{\eta^*_{R_{i_l}}} \left(\frac{x^2}{C} \right) dx$$

According to (18), the above formula can be rewritten as:

$$\begin{aligned} {}_S^D P_e = \int_0^\infty & \left(\sum_{M=1}^{L} C_L^M \prod_{i_m \in \Psi'} \left(1 - e^{-\omega_{i_m} I_{th}}\right) \prod_{s_n \in \Phi' - \Psi'} \left(e^{-\omega_{s_n} I_{th}}\right) \right) \\ & \cdot \left(\prod_{i_m \in \Psi'} \left[1 - \left(\frac{C\beta_{i_m}}{\lambda_{i_m} \cdot x^2 + C\beta_{i_m}} e^{\frac{-\lambda_{i_m} x^2}{C}} \right) \left(e^{\frac{-\alpha_{i_m} x^2}{C}} \right) \right] \right) \cdot \frac{1}{\sqrt{2\pi}} e^{-\frac{x^2}{2}} dx \\ = \frac{1}{\sqrt{2\pi}} & \sum_{M=1}^{L} C_L^M \prod_{i_m \in \Psi'} \left(1 - e^{-\omega_{i_m} I_{th}}\right) \cdot \prod_{s_n \in \Phi' - \Psi'} \left(e^{-\omega_{s_n} I_{th}}\right) \cdot \int_0^\infty \prod_{i_m \in \Psi'} e^{\frac{-x^2}{2}} \cdot \left[1 - \left(\frac{C\beta_{i_m}}{\lambda_{i_m} x^2 + \beta_{i_m} C} e^{\frac{-\lambda_{i_m} x^2}{C}} \right) \cdot \left(e^{\frac{-\alpha_{i_m} x^2}{C}} \right) \right] dx \end{aligned} \tag{20}$$

5. Numerical Simulation

We analyse IBRSS performance in L = 3 and L = 6 scenarios and compare IBRSS with BRSS and direct communication. The influence of interference on secondary networks performance is studied. Fig. 2 presents OP of IBRSS, BRSS and direct communication when $I_{th} = 27dB$. With the increase of $\hat{\gamma}_S^{R_l}$, regardless of IBRSS, BRSS or direct communication, OP is gradually reduced. In the low SNR range, the IBRSS OP of $L = 3$ situation is better than that of $L = 6$ situation. The opposite is true in high SNR range.

Fig. 3 presents OP of IBRSS, BRSS with different values of L, I_{th}. Our results show that OP of SNs increases with increase in $\hat{I}_P^{R_l}$. This indicates that in the system with mutual interference, the performance of the secondary networks will be worse because of the interference of the primary networks. IBRSS is less affected by PNs interference and has lower OP than the BRSS. This indicates that IBRSS can reduce the impact of interference on secondary networks performance, and the performance of IBRSS is more stable than that of BRSS and direct communication.

Fig. 4 presents the BER of IBRSS, BRSS with different values of L and I_{th}. The results show that IBRSS has a lower BER than BRSS. For the IBRSS, the BER decreases with the increase in values of I_{th} and L. The BER of $L=6, I_{th}=30dB$ situation is much smaller than $L=6, I_{th}=27dB$ situation.

For simplicity of calculation, we will consider the number of relays that need to be traversed as CSI requirements. Fig. 5 presents the CSI of IBRSS, BRSS. When the power increases gradually, some relay nodes can't meet the interference limit, so the number of potential relay nodes decreases. IBRSS traverses fewer relay nodes and CSI requirements are reduced. When $P_R = 50dBW$, the demand of BRSS for CSI is more than three times that of IBRSS.

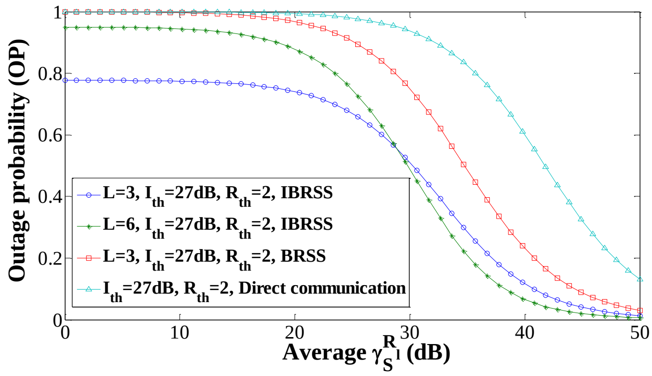

Fig. 2. The OP of IBRSS, BRSS and direct communication when $I_{th} = 27dB$, $R_{th} = 2$

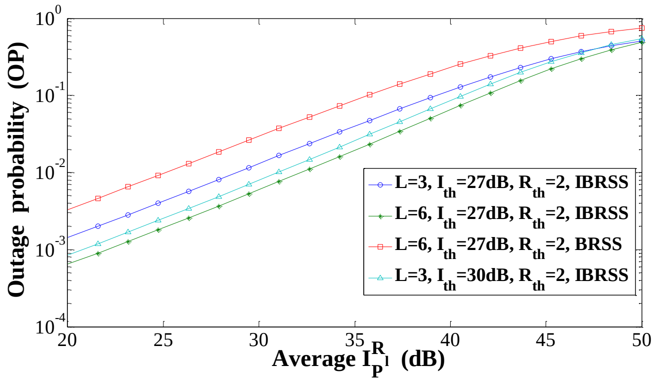

Fig. 3. The OP of IBRSS, BRSS with different values of L and I_{th}

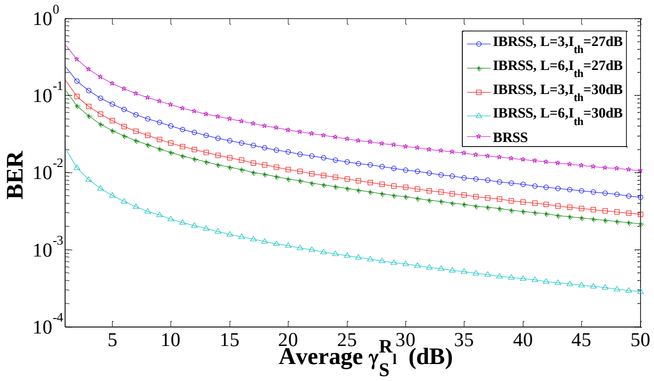

Fig. 4. The BER of IBRSS, BRSS with different values of L and I_{th}

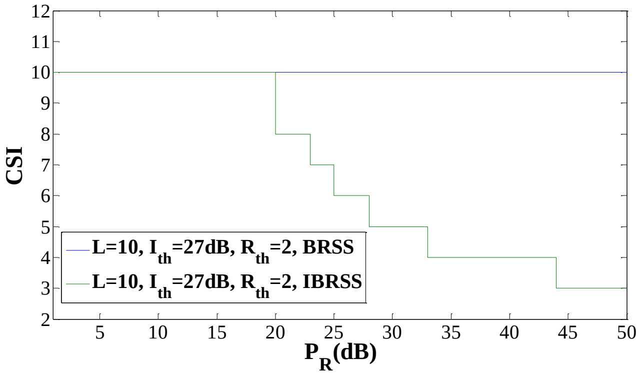

Fig. 5. The quantity demanded for CSI when $I_{th} = 15dB$

6. Conclusions

In this paper, a system model of mutual interference between PNs and SNs is introduced, and the channel gains of relays are assumed to be independent differently distributed. We introduced IBRSS that effectively improves the performance of SNs and reduces the demand of CSI. Through analysis and simulation, we find that IBRSS can effectively improve the performance of SNs and has lower OP and BER than BRSS and direct communication. The interference of PNs to relays will deteriorate the performance of SNs. When interference is very strong, the node S cannot transmit data to node D. Therefore, when analysing and calculating the SINR, the interference needs to be considered. The SINR should not be modelled as an exponential distribution.

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