Decode-and-Forward Full-Duplex Relay Selection Under Rayleigh Fading Environment

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Abstract. In this paper, under Rayleigh fading environment, we focus on the relay selection problem in the multiple full-duplex (FD) relay networks consisting of one source, one destination, and N FD decode-and-forward (DF) relays. The optimal relay selection that requires global channel state information (CSI) and three suboptimal relay selection schemes that utilize partial CSI are discussed over independent- and identically- distributed (I.I.D.) Rayleigh fading channels. Moreover, to facilitate analysis, outage probability expressions of these schemes are derived. Then, Comparing DF protocol with amplify-to-forward protocol (AF), numerical results show that DF-relay can achieve a better performance. Besides, the effects of self-interference-to-noise ratio (INR) and the number of relay on outage probability for different selection schemes are investigated. Correspondingly, the best suboptimal scheme and relay arrangement policy have been obtained. Finally, Monte-Carlo simulations are performed to demonstrate the validity of the analytical results.

Keywords: Full-duplex relay selection · Decode-and-forward
Outage probability · Fading channels

1 Introduction

In recent years, cooperative communication technology has attracted massive attention of researchers throughout the world. It can expand coverage area, reach larger system capacity and obtain higher spectrum efficiency [1–3]. For traditional half-duplex (HD) mode, relays retransmit the source data in orthogonal and dedicated channels. Hence, the system spectrum efficiency would be reduced by 50% [4,5]. In order to conquer spectrum loss, FD relay is preferred in recent researches. However, FD mode has been considered impractical in the

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past due to the self-interference caused by signal leakage between the relay output and input. But recent advanced self-interference elimination techniques make it feasible [6–8].

On account of the unstable channel environment for a single relay system, multiple relay system has been adopted to further improve performance [9]. Thus, how to select an optimal relay from many candidates has become an advanced research hotspot [10]. Accordingly, a research proves that selects an optimal relay for transmission is the ideal solution to balance diversity gain and spectrum efficiency [11].

Nowadays, most of the relay receives and retransmits the signal by two kinds of relaying protocol, namely, amplify-to-forward protocol (AF) and decode-to-forward protocol (DF). The principle of AF relay is that amplifying the received signal in accordance with a specific coefficient, and forwards it to destination node without other processing. Therefore, using AF-relay for communication has the advantage that system design is relatively simple, easy to implement, and the deployment cost is low. Therefore, most of the researcher studies on it. In [12], different relay selection policies are proposed in FD AF relay networks. In addition, exact outage probability expressions and asymptotic approximations of these policies that show a zero diversity order are derived. Moreover, the authors of [13] proposes a joint relay and antenna selection scheme in general full-duplex (FD) relay networks with one source, one destination and N FD AF relays. In addition, relay selection technique in the two-way FD relay system using AF protocol is analyzed, and the exact expressions of bit error rate (BER), ergodic capacity and outage probability are derived [14].

However, the amplified signal at AF relay node contains not only the signal effectively, also contains a certain amount of noise, which will make performance degradation. In order to overcome the aforementioned problem, some researchers try to study the optimal and partial relay selection schemes in FD DF relay networks, which assume the self-interference channel is non-fading for simplified analysis [15,16]. However, there is no previous work on FD relay selection scheme over I.I.D. Rayleigh fading channels. And the comparison between AF protocol and DF protocol is missing. In this paper, an optimal and three suboptimal relay selection schemes are discussed in a multiple FD DF relay networks over I.I.D. Rayleigh fading channels firstly. Then, outage probability of these schemes is derived. Finally, compared to AF protocol, numerical results are presented to show a better performance of DF protocol. Furthermore, effects of INR and the number of relay on outage probability are analyzed. Then, the best suboptimal scheme and relay arrangement policy are given.

This paper is organized as follows: Sect. 2 sets up the system model. Section 3 deals with different relay selection schemes and the outage probability is derived. Simulation and analytical results are presented in Sect. 4, and are followed by conclusions in Sect. 5.

2 System Model

2.1 System Model

We consider a system with one source (S), one destination (D) and N relay nodes between the source and destination. The direct link between the source and destination is assumed to be unreliable due to a large distance between them. The S and D nodes operate on HD mode and are equipped with a single antenna. However, each relay node is equipped with two antennas, one receiving antenna and one transmitting antenna, enabling an FD operation at the price of self-interference.

The channel coefficients are assumed to be independent and identically distributed (i.i.d) complex Gaussian random variables. Let h_{AB_k}, $\{A, B\} \in \{S, R, D\}$, denotes the channel gain from S node to relay k, $S \rightarrow R_k$, and from relay k to D, node, $R_k \rightarrow D$, as well as from relay k output to relay k input, $R_k \rightarrow R_k$, with zero mean and variance δ_{AB_k}. Therefore, the magnitude of channels h_{AB_k} is Rayleigh distributions which follows the probability density function (PDF) of power channel gains, $|h_{AB_k}|^2$, to be an exponential distribution with parameters λ_{AB_k}. Additionally, we assume all noise terms have additive Gaussian noise (AWGN) with zero mean and equal variance, where power noise is denoted by N_0 (Fig. 1).

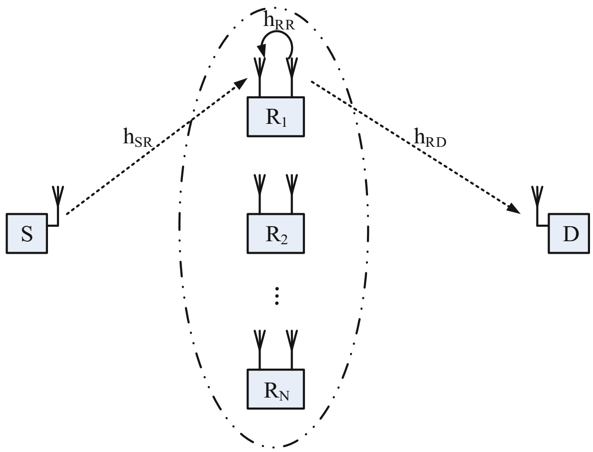

Fig. 1. System model of full-duplex DF-relay system

The proposed system model can be regarded as two phases. In phase-1, $S \rightarrow \overleftarrow{R}_k \cdots D$, S continuously transmits its information symbol x_S to N relay nodes. Simultaneously, a relay node forwards the decoded-signal x_R from the previous time slot, which imposes self-interference denoted as $\overleftarrow{R}_k$. Thus, the received signal at relay k can be written as

$$y_{R_k} = \sqrt{P_S} h_{SR_k} x_S + \sqrt{P_R} h_{RR_k} x_R + n_{R_k} \quad (1)$$

where P_S and P_R represent the transmit power at the source and relay respectively. n_{R_k} represents additive Gaussian noise at relay. So, SNR $\gamma_{SR_k} = P_S|h_{SR_k}|^2/N_0$, INR $\gamma_{RR_k} = P_R|h_{RR_k}|^2/N_0$. Accordingly, the instantaneous signal-to-interference plus noise ratio (SINR) for the $S - R_k$ link is given as $\gamma_{R_k} = \gamma_{SR_k}/(\gamma_{RR_k} + 1)$.

In phase-2, $S \cdots \overleftarrow{R}_k \rightarrow D$, a single relay (the best relay) among N relay nodes providing the best end-to-end transmission path is selected to transmit the source signal to the destination. Meanwhile, N relay nodes receive a signal from the next time slot. Thus, the received signal at the destination is expressed as

$$y_D = \sqrt{P_R} h_{R_k D} x_R + n_D \tag{2}$$

n_D represents additive Gaussian noise at destination. And, the SNR $\gamma_{R_k D} = P_R|h_{R_k D}|^2/N_0$.

Correspondingly, the capacity of the system can be written as

$$C = \log_2(1 + \min\{\gamma_{R_k}, \gamma_{R_k D}\}) \tag{3}$$

3 FD DF-Relay Selection Scheme over I.I.D. Rayleigh Fading Channels

In this section, the optimal relay selection that requires global CSI and three suboptimal relay selection schemes that utilize partial CSI are discussed in FD DF relay networks over I.I.D. Rayleigh fading channels. Then, exact expressions of outage probability for these schemes are derived. By considering the definition of outage probability, the undefined expressions can be written as:

$$\begin{aligned} P_* &= \Pr\{\log_2(1 + \min\{\gamma_{R_k}, \gamma_{R_k D}\}) < R_0\} \\ &= \Pr\{\min\{\gamma_{R_k}, \gamma_{R_k D}\} < 2^{R_0} - 1 = u\} \\ &= F_{\gamma_{eq}}(u) \end{aligned} \tag{4}$$

The * refers to different relay selection schemes, and Pr denotes the probability. In order to simplify notation, we define $\gamma_{eq} = \min\{\gamma_{R_k}, \gamma_{R_k D}\}$. $F_{\gamma_{eq}}(\cdot)$ is the CDF (Cumulative Distribution Function) of the random variables.

3.1 Optimal Relay Selection (OS)

Based on a full duplex channel capacity expression, the optimal relay selection scheme is easily obtained. According to the formula Eq. (3), the best relay k is selected, and it is performed as follow:

$$k_{OS} = \arg\max_k\{\min\{\gamma_{R_k}, \gamma_{R_k D}\}\} \tag{5}$$

For a Rayleigh fading channel, the PDF of γ_{AB} is given by

$$f_{\gamma_{AB}}(x) = \lambda_{AB} e^{-\lambda_{AB} x}, x \geq 0 \tag{6}$$

Then, the CDF of γ_R can be derived as

$$F_{\gamma_R}(x) = \Pr\{\gamma_R < x\} = \Pr\{\frac{\gamma_{SR}}{\gamma_{RR}+1} < x\} \tag{7}$$

Since γ_{SR} and γ_{RR} are independent of each other, the joint PDF γ_{SR} and γ_{RR} can be expressed as:

$$f_{\gamma_{SR},\gamma_{RR}}(x,y) = \lambda_{SR}\lambda_{RR}e^{-\lambda_{SR}x-\lambda_{RR}y}, x \geq \&y \geq 0 \tag{8}$$

According to probability theory, $F_{\gamma_R}(x)$ can be shown as

$$\begin{aligned} F_{\gamma_R}(x) &= \int_0^{+\infty}\int_0^{(1+\gamma_{RR})x} f(\gamma_{SR},\gamma_{RR})d\gamma_{SR}d\gamma_{RR} \\ &= 1 - \frac{1}{1+\frac{\lambda_{SR}}{\lambda_{RR}}x}e^{-\lambda_{SR}x}, x \geq 0 \end{aligned} \tag{9}$$

Furthermore, by denoting $Z = \min\{\gamma_R, \gamma_{RD}\}$, the CDF of Z can be derived as

$$F_Z(x) = 1-(1-F_{\gamma_R}(x))(1-F_{\gamma_{RD}}(x)), x \geq 0 \tag{10}$$

From Eq. (6), $F_{\gamma_{RD}}(x) = 1-e^{-\lambda_{RD}x}$ can be obtained, and contact with Eq. (9), the CDF of Z can be expressed as

$$F_Z(x) = 1 - \frac{1}{1+\frac{\lambda_{SR}}{\lambda_{RR}}x}e^{-(\lambda_{SR}+\lambda_{RR})x}, x \geq 0 \tag{11}$$

Leading to

$$F_{\gamma_{eq}}(x) = [F_Z(x)]^N, x \geq 0 \tag{12}$$

3.2 Partial Relay Selection (PS)

Supposing only can CSI of first jump and relay output to input be got, then the optimal DF-relay is chosen. That is partial relay selection scheme with largest SINR. Hence, the best relay k is performed as follow:

$$k_{PS} = \arg\max_k\{\gamma_{R_k}\} \tag{13}$$

For PS scheme, through Eq. (9) and order statistics theory, the CDF of SINR for the $S-R_k$ link can be given by

$$\begin{aligned} F_{\gamma_R}(x) &= [1 - \frac{1}{1+\frac{\lambda_{SR}}{\lambda_{RR}}x}e^{-\lambda_{SR}x}]^N, x \geq 0 \\ &= \sum_{n=0}^{N}(-1)^n\frac{1}{(1+\frac{\lambda_{SR}}{\lambda_{RR}}x)^n}e^{-\lambda_{SR}nx}, x \geq 0 \end{aligned} \tag{14}$$

The above deducing process applies the fact that $(1-x)^n = \sum_{n=0}^{N} \binom{N}{n} (-1)^n x^n$. Then, the CDF of SNR for the $S - R_k - D$ link can be given by

$$\begin{aligned} F_{\gamma_{eq}}(x) &= 1 - (1 - F_{\gamma_R}(x))(1 - F_{\gamma_{RD}}(x)), x \geq 0 \\ &= \sum_{n=1}^{N} (-1)^{n-1} \frac{1}{(1 + \frac{\lambda_{SR}}{\lambda_{RR}} x)^n} e^{-(\lambda_{SR} n + \lambda_{RD})x}, x \geq 0 \end{aligned} \tag{15}$$

3.3 Max-Min Relay Selection (MM)

In a conventional half-duplex relay system, the influence of self-interference is not taken into consideration in the optimal relay selection scheme. Applying to full duplex relay system, the best relay k is performed as follow:

$$k_{MM} = \arg\max_k \{\min\{\gamma_{SR_k}, \gamma_{R_k D}\}\} \tag{16}$$

Ignoring the interference, the MM scheme is based on the link of $S - R$ and $R - D$. Then, using basic probability theory and symmetry, $F_{\gamma_{SR_k}}(x)$ can be written as

$$\begin{aligned} F_{\gamma_{SR_k}}(x) &= N \times \Pr\{\gamma_{SR_i} < x \cap k = i\} \\ &= N \int_0^x \Pr\{k = i | \gamma_{SR_i} = y\} f_{\gamma_{SR}}(y) dy \end{aligned} \tag{17}$$

There are two cases should be taken into account, $\gamma_{SR} > \gamma_{RD}$ and $\gamma_{SR} < \gamma_{RD}$. According to [17], $F_{\gamma_{SR_k}}(x)$ can be expressed as

$$\begin{aligned} F_{\gamma_{SR_k}}(x) = N(&\frac{1 - e^{-\lambda_{SR} x}}{\lambda_{SR} + \lambda_{RD}} \sum_{n=0}^{N-1} \frac{(-1)^n \binom{N-1}{n}}{\frac{n}{\lambda_{RD}} + \frac{1}{\lambda_{SR} + \lambda_{RD}}} \\ &- \frac{\lambda_{SR}}{\lambda_{SR} + \lambda_{RD}} \sum_{n=0}^{N-1} (-1)^n \binom{N-1}{n} \\ &\times \frac{(1 - e^{-(n+1)(\lambda_{SR} + \lambda_{RD})x})}{(\frac{n}{\lambda_{RD}} + \frac{1}{\lambda_{SR} + \lambda_{RD}})(n+1)(\lambda_{SR} + \lambda_{RD})} \\ &+ \lambda_{SR} \sum_{n=0}^{N-1} \frac{(-1)^n \binom{N-1}{n} (1 - e^{-(n+1)(\lambda_{SR} + \lambda_{RD})x})}{(n+1)(\lambda_{SR} + \lambda_{RD})}) \end{aligned} \tag{18}$$

Using Eq. (18), the required CDF of $F_{\gamma_R}(x) = \lambda_{RR}\int_0^\infty F_{\gamma_{SR_k}}((y+1)x)e^{-\lambda_{RR}y}dy$ can be calculated as

$$\begin{aligned} F_{\gamma_R}(x) = {} & \frac{N}{\lambda_{SR}+\lambda_{RD}}[\sum_{n=0}^{N-1}\frac{(-1)^n\binom{N-1}{n}}{\frac{n}{\lambda_{RD}}+\frac{1}{\lambda_{SR}+\lambda_{RD}}} \\ & \times(1-\frac{1}{1+\frac{\lambda_{SR}}{\lambda_{LI}}x}e^{-\lambda_{SR}x}) - \frac{\lambda_{SR}}{\lambda_{SR}+\lambda_{RD}}\sum_{n=0}^{N-1}(-1)^n \\ & \times\binom{N-1}{n}\frac{(1-\frac{e^{-(n+1)(\lambda_{SR}+\lambda_{RD})x}}{1+\frac{(n+1)(\lambda_{SR}+\lambda_{RD})x}{\lambda_{LI}}})}{(\frac{n}{\lambda_{RD}}+\frac{1}{\lambda_{SR}+\lambda_{RD}})(n+1)} \\ & +\lambda_{SR}\sum_{n=0}^{N-1}\frac{(-1)^n\binom{N-1}{n}(1-\frac{e^{-(n+1)(\lambda_{SR}+\lambda_{RD})x}}{1+\frac{(n+1)(\lambda_{SR}+\lambda_{RD})x}{\lambda_{LI}}})}{(n+1)}] \end{aligned} \tag{19}$$

Then, the CDF of $F_{\gamma_{R_kD}}(x)$ can be obtained from Eq. (18) by mutually exchanging λ_{SR} and λ_{RD} to yield

$$\begin{aligned} F_{\gamma_{RD}}(x) = N(& \frac{1-e^{-\lambda_{RD}x}}{\lambda_{SR}+\lambda_{RD}}\sum_{n=0}^{N-1}\frac{(-1)^n\binom{N-1}{n}}{\frac{n}{\lambda_{SR}}+\frac{1}{\lambda_{RD}+\lambda_{SR}}} \\ & -\frac{\lambda_{RD}}{\lambda_{RD}+\lambda_{SR}}\sum_{n=0}^{N-1}(-1)^n\binom{N-1}{n} \\ & \times\frac{(1-e^{-(n+1)(\lambda_{SR}+\lambda_{RD})x})}{(\frac{n}{\lambda_{SR}}+\frac{1}{\lambda_{SR}+\lambda_{RD}})(n+1)(\lambda_{SR}+\lambda_{RD})} \\ & +\lambda_{RD}\sum_{n=0}^{N-1}\frac{(-1)^n\binom{N-1}{n}(1-e^{-(n+1)(\lambda_{SR}+\lambda_{RD})x})}{(n+1)(\lambda_{SR}+\lambda_{RD})}) \end{aligned} \tag{20}$$

Finally, substituting Eqs. (19) and (20) into Eq. (10) to calculates exact outage probability.

3.4 Self-interference Relay Selection (SI)

Since the self-interference relay selection scheme only considers the interference, it's easy to get the best relay k:

$$k_{SI} = \arg\min_k\{\gamma_{RR_k}\} \tag{21}$$

For SI scheme, Relay selection is only related to the self-interference. According to the order statistics, the CDF of the self-interference can be given by

$$F_{\gamma_{RR_k}}(x) = (1-(1-F_{\gamma_{RR}}(x))^N), x \geq 0 \tag{22}$$

Taking a derivative of $F_{\gamma_{RR_k}}(x)$, $f_{\gamma_{RR_k}}(x) = N\lambda_{RR}e^{-N\lambda_{RR}x}$. Like Eq. (9), jointing $f_{\gamma_{RR_k}}(x)$ and $f_{\gamma_{SR}}(x)$, the CDF of γ_R can be expressed as

$$F_{\gamma_{R_k}}(x) = 1 - \frac{1}{1 + \frac{\lambda_{SR}}{N\lambda_{RR}}x}e^{-\lambda_{SR}x}, x \geq 0 \tag{23}$$

Finally joining the SNR of $R_k - D$ link, through some reduction, the CDF of system's SNR can be given by

$$\begin{aligned} F_{\gamma_{eq}}(x) &= [1 - (1 - F_{\gamma_{R_k}}(x))(1 - F_{\gamma_{RD}}(x))] \\ &= \frac{1}{1 + \frac{\lambda_{SR}}{N\lambda_{RR}}x}e^{-(\lambda_{SR}+\lambda_{RD})x}, x \geq 0 \end{aligned} \tag{24}$$

4 Numerical and Simulation Results

In this Section, numerical examples for the outage probability are presented. The simulation system follows the system model of Sect. 2 with $R_0 = 2BPCU$, and the considered relay selection schemes are: OS, PS, MM and SI.

Figure 2 plots outage probability curves along with the change of γ_{SR} with $N = 3$, $\lambda_{RR} = 1$ and $\lambda_{RD} = \lambda_{SR}$. It proves that the performance of DF-relay is always better than AF-relay. The reason is that DF-relay recodes and modulates the received signal to avoid the system noise and error accumulation spread. However, DF-relay system and AF-relay system come to the same level as γ_{SR} growing, because the effect of the noise on the first link can be neglected when γ_{SR} is lager enough.

Figure 3 shows outage probability as a function of INR for the different relay selection schemes with $N = 3$, $\lambda_{SR} = \lambda_{RD} = 0.01$. As you can see, OS scheme is

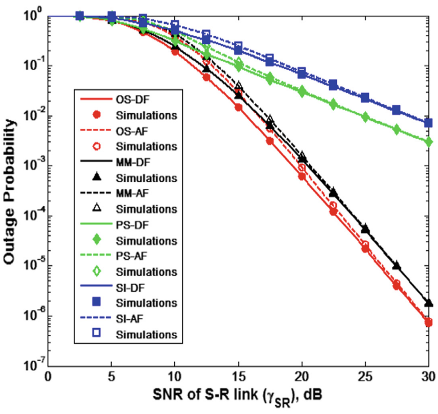

Fig. 2. Outage probability versus γ_{SR}, $N = 3$, $\gamma_{RD} = \gamma_{SR}$, $\lambda_{RR} = 1$.

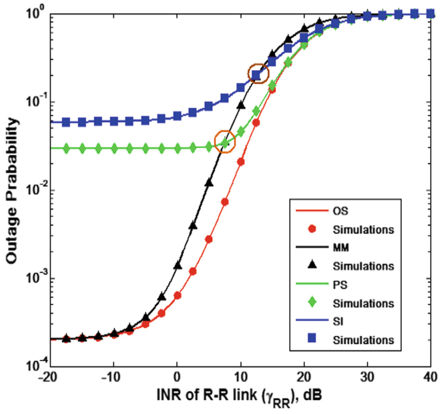

Fig. 3. Outage probability versus INR γ_{RR}, $N = 3$, $\lambda_{SR} = \lambda_{RD} = 0.01$.

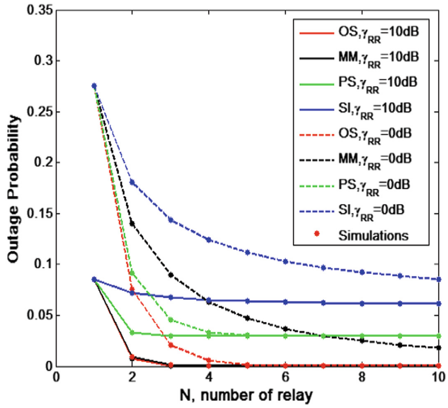

Fig. 4. Outage probability versus number of relay N, $\lambda_{SR} = \lambda_{RD} = 0.01$.

always the best one, but MM scheme close to it. PS scheme is always better than SI scheme, because PS scheme takes γ_{RR} into account additionally. Moreover, there are two points of intersection as γ_{RR} becomes more and more impactive. Therefore, when self-interference belongs to the lower levels, MM scheme can be used as an alternative to OS scheme. Accordingly, when self-interference at a higher level, OS scheme can be replaced by PS scheme.

Figure 4 presents the change of outage probability following the number of relay N with $\lambda_{RR} = 1$ or $\lambda_{RR} = 0.1$, and $\lambda_{SR} = \lambda_{RD} = 0.01$. The outage probability will be lower when N becomes lager. But it will reach to a saturation value. Therefore, we can obtain best performance by deploying limited relays.

In the three picture, it can be seen that the analytical results are in good agreement with results obtained from Monte-Carlo simulations.

5 Conclusion

This paper has dealt with the problem of relay selection for the multiple FD relay networks consisting of one source, one destination, and N FD DF relays over I.I.D. Rayleigh fading channels. Firstly, the optimal and three suboptimal relay selection schemes requiring global CSI or partial CSI have been investigated respectively. Then, the relay selection schemes have been analyzed in terms of outage probability. Compared to AF protocol, numerical results show the superiority of DF protocol. Besides, the best suboptimal relay selection scheme substituted for OS scheme and the relay arrangement policy have been presented.

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