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A Simple N^{th} Best-Relay Selection Criterion for Opportunistic Two-Way Relay Networks under Outdated Channel State Information

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Abstract

The frequency spectrum available for the wireless communication is extremely crowded. In order to improve the spectral efficiency, the two-way relay networks have aroused great attention. A simple N^{th} best-relay selection criterion for the opportunistic two-way relay networks is proposed, which can be implemented easily by extending the distributed timer technique in practice, since the proposed criterion is mainly based on the channel gains. The outage performance of the proposed relay selection scheme is analyzed under the outdated channel state information (CSI), and a tight closed-form lower bound and asymptotic value of the outage probability over Rayleigh fading channels are obtained. Simulation results demonstrate that the tight closed-form lower bound of the outage probability very closely matches with simulated ones in the whole SNR region, and the asymptotic results provide good tight approximations to the simulation ones, especially in the high SNR region.

Keywords: Cooperative communications, two-way relay networks, relay selection, analog network coding (ANC), outdated channel state information (CSI), outage probability

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1. Introduction

In recent years, the cooperative diversity [1] applied in wireless communication systems has aroused great attention, based on the work of the relay channels [2] and the multiple access channels [3]. The basic principle of the cooperation is that the single-antenna nodes share their antennas and transmit cooperatively in a way that creates a virtual MIMO system. In comparison with the non-cooperative systems, the cooperative systems has more robustness, and can supply higher rate of the data transmission. Therefore, the cooperation is desirable in the practical wireless sensor networks [4, 5], cognitive radio networks [6-8] or ad hoc systems [9], which have rigorous limitations of size, cost and consumption.

Among various cooperative techniques, the opportunistic relay selection [10, 11], where the best relay is activated, is one of the most efficient schemes to utilize spatial diversity, especially for the cooperative networks with a large number of relays; however, in the conventional one-way relay networks, four time slots are required for the exchange of the one information symbol between two source S and D nodes with the help of relays, since all terminals are operated in the half-duplex fashion, as shown in **Fig. 1.**

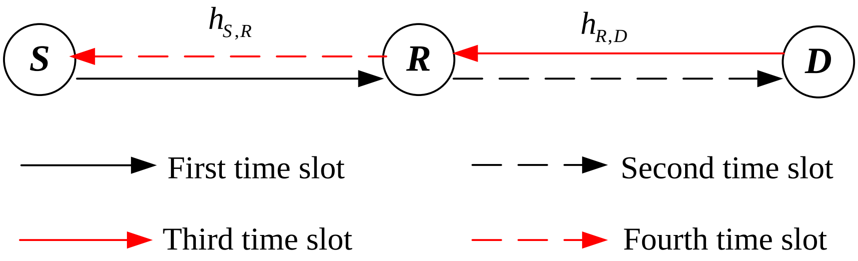

Fig. 1. System model for one-way relay networks with one relay node, S and D: transceivers, R: relay, $h_{S,R}$ and $h_{R,D}$: reciprocal channel response

With the aim of improving the spectral efficiency, the two-way-relaying scheme is proposed in [12], where one or multiple relays are employed to implement reliable bidirectional communications between the two transceivers. The two-way relay network with one relay node is demonstrated in **Fig. 2**, where the simultaneous data exchange is completed between two source nodes S and D in two time slots. To improve the performance of the two-way relaying system, some new two-way relay selection schemes are presented in [13-17], which adopt either analog network coding (ANC) based on the amplify-and-forward (AF) or physical layer network coding (PLNC) based on decode-and-forward (DF) protocols, and the outage performance or pairwise error probability of two-way relay networks is also investigated in [18-20].

On the other hand, most previous researches assume that the channel state information (CSI) is perfect; however, when relay selection is implemented in real systems, there may be a possibility that the channel state of the selected relay at the selection decision phase substantially differs from the actual channel of the data transmission, due to channel variations with time, feekback delay, or the channel estimation error. In other words, the available CSI may be outdated, which leads to the system performance loss. There have been emerging attentions on researching cooperative communication system under the outdated CSI. The one-way relay networks with outdated CSI, for instance, are widely researched [21-25]. In very recent years, some efforts are also put into the two-way relay networks with outdated CSI, based on the single relay or multiple relay selection [26-28]. In [27], the outage performance of the two-way AF relaying system with outdated CSI is studied. In [28], a multiple relay selection scheme for AF based on two-way relay networks with outdated CSI is proposed.

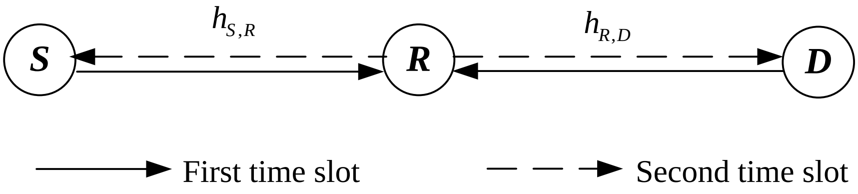

Fig. 2. System model for two-way relay networks with one relay node, *S* and *D*: transceivers, *R*: relay, $h_{S,R}$ and $h_{R,D}$: reciprocal channel response

For the schemes of the single relay selection, the selected best relay, however, might be unavailable due to various reasons in the real system, such as load balancing and scheduling issues; hence, the second best relay, the third best relay, or more generally, the N^{th} best relay has to be adopted, in order to guarantee the networks operate well. Hence, the scheme of the N^{th} best-relay selection is proposed to adopt the N^{th} best relay, when the best relay may be unavailable, in the opportunistic two-way relay networks. In the paper, it is assumed that the CSI in the data transmission phase differs (i.e., is outdated) from that in the relay selection phase, while the CSI is invariant in each phase separately, from a practical point of view. The impact of the outdated CSI on the network is discussed over Rayleigh fading channels by obtaining a tight closed-form lower bound of the outage probability. Simulation results are also given to support the analytical results, which show that the analytical results are very close to the simulated ones in the whole SNR regime, and the asymptotic results well match the simulated ones, especially in the high SNR regime.

The rest of the paper is organized as follows. Section 2 characterizes the system model, and the proposed relay selection scheme. The outage performance under outdated CSI is analyzed in Section 3. In Section 4, simulation results are demonstrated. The conclusion of the paper is given in Section 5.

2. Relay Selection Scheme

2.1 System Model

Consider an ANC-based opportunistic two-way relay network consisting of two transceivers and M relays, denoted by S, D and R_m, $m = 0,1,...,M-1$, respectively, as illustrated in **Fig. 3**. All nodes are single-antenna units and operate in a half-duplex mode. No direct communication is assumed between the two transceivers S and D, due to the poor quality of the channel. In order to analyze conveniently, it is assumed that the distances d_{S,R_m} between node S and any relay R_m are the same, and then we can obtain that the distributions of the channel response h_{S,R_m} are identical, denoted as $h_{S,R_m} \sim CN(0, d_{S,R_m}^{-\alpha})$ with the path loss α. Similarly, $h_{R_m,D} \sim CN(0, d_{R_m,D}^{-\alpha})$ is acquired, where $d_{R_m,D}$ is the distances between node D and any relay R_m. Without loss of generality, the normalized distances d_{S,R_m} and $d_{R_m,D}$ are employed, satisfying $d_{S,R_m} + d_{R_m,D} = 1$.

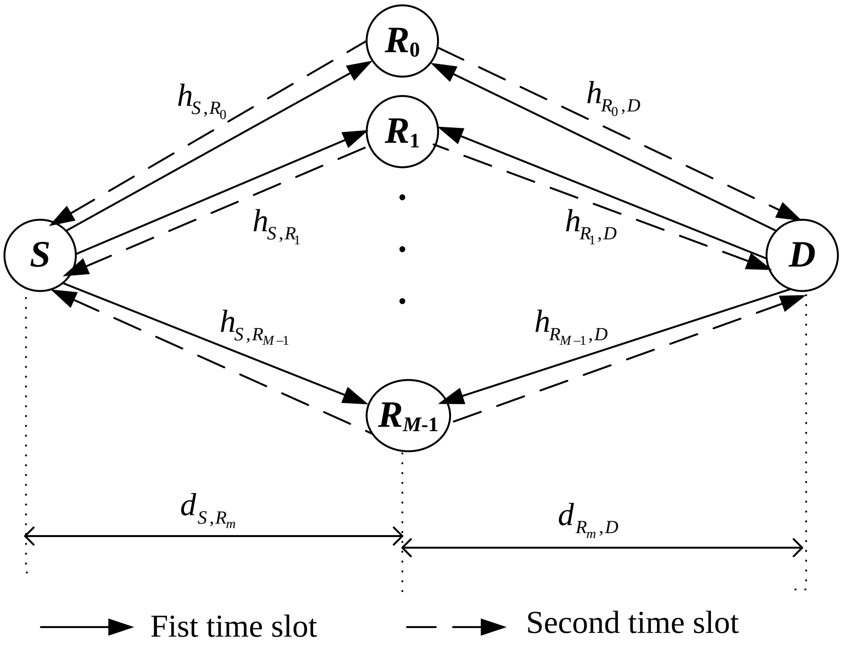

Fig. 3. System model of opportunistic two-way relay network with M relay nodes, S and D: transceivers, R_m ($m = 0,1,...,M-1$): relays, h_{S,R_m} and $h_{R_m,D}$: reciprocal channel response, normalized distance $d_{S,R_m} + d_{R_m,D} = 1$

The relay selection phase in the proposed opportunistic two-way-relaying system consists of two steps. In the first time slot, the S and D transit their signal to the relays, simultaneously, as shown in **Fig. 3.** Let x_S and x_D be the information symbols transmitted by the S and D, respectively. With perfect synchronization, the received signal y_m of the m^{th} relay can be represented as

$$y_m = \sqrt{P_S} h_{S,R_m} x_S + \sqrt{P_D} h_{R_m,D} x_D + n_m \tag{1}$$

where P_S and P_D are the transmit powers of the S and D, respectively, and $n_m \sim CN(0, N_0)$ is the complex Gaussian noise with the zero mean and variance N_0.

At the second time slot, the m^{th} relay amplifies and retransmits the received signal to the S and D. Then the received signals at the S and D are given, respectively, by

$$y_S' = G\sqrt{P_S} h_{S,R_m}^2 x_S + G\sqrt{P_D} h_{S,R_m} h_{R_m,D} x_D + G h_{S,R_m} n_m + n_{mS} \tag{2}$$

$$y_D' = G\sqrt{P_S} h_{S,R_m} h_{R_m,D} x_S + G\sqrt{P_D} h_{R_m,D}^2 x_D + G h_{R_m,D} n_m + n_{mD} \tag{3}$$

where the amplifying coefficient

$$G = \sqrt{P_R / (P_S \left|h_{S,R_m}\right|^2 + P_D \left|h_{R_m,D}\right|^2 + N_0)} \tag{4}$$

P_R is the transmission power of R_m, and n_{mS} and n_{mD} are the complex Gaussian noise with zero mean and variance N_0, that is, $n_{mS} \sim CN(0, N_0)$ and $n_{mD} \sim CN(0, N_0)$.

Assuming that the self-interference can be removed completely, the signals $y_S^{'}$ and $y_D^{'}$ after the self-interference cancellation are written, respectively, as

$$y_S = G\sqrt{P_D}\, h_{S,R_m} h_{R_m,D} x_D + G h_{S,R_m} n_m + n_{mS} \tag{5}$$

$$y_D = G\sqrt{P_S}\, h_{S,R_m} h_{R_m,D} x_S + G h_{R_m,D} n_m + n_{mD}. \tag{6}$$

The residual signals y_S and y_D can be uesd to decode the information symbols x_S and x_D at D and S, respectively. According to (5) and (6), the end-to-end SNRs of the links $D \to R_m \to S$ and $S \to R_m \to D$ are given, respectively, as

$$\gamma_{DmS} = \frac{\frac{P_R}{N_0}\left|h_{S,R_m}\right|^2 \frac{P_D}{N_0}\left|h_{R_m,D}\right|^2}{\frac{P_R + P_S}{N_0}\left|h_{S,R_m}\right|^2 + \frac{P_D}{N_0}\left|h_{R_m,D}\right|^2 + 1} \tag{7}$$

$$\gamma_{SmD} = \frac{\frac{P_R}{N_0}\left|h_{R_m,D}\right|^2 \frac{P_S}{N_0}\left|h_{S,R_m}\right|^2}{\frac{P_R + P_D}{N_0}\left|h_{R_m,D}\right|^2 + \frac{P_S}{N_0}\left|h_{S,R_m}\right|^2 + 1}. \tag{8}$$

2.2 Proposed Relay Selection Scheme

The optimal relay selection criterion, which maximizes the minimum of the two end-to-end SNRs, is written as [29]:

$$m* = \arg \max_{m \in \{0,1,\ldots,M-1\}} \min\{\gamma_{DmS}, \gamma_{SmD}\}. \tag{9}$$

It can be observed from (9) that the optimal relay selection criterion is based on instantaneous end-to-end SNRs γ_{DmS} and γ_{SmD}, and requires continuous CSI feedback from all the links of the network, in other words, the criterion can only be implemented in a centralized manner, which is difficult to be realized in practice. Since the end-to-end SNRs γ_{DmS} and γ_{SmD} are difficult to be analyzed straightforwardly, the more tractable results are obtained, based on (7) and (8), which can be expressed as

$$\frac{1}{\gamma_{DmS}} = \frac{1}{\frac{P_R}{N_0} \cdot \frac{P_D}{P_R + P_S} \cdot \left|h_{R_m,D}\right|^2} + \frac{1}{\frac{P_R}{N_0} \cdot \left|h_{S,R_m}\right|^2} + \frac{1}{\frac{P_R}{N_0}\left|h_{S,R_m}\right|^2 \frac{P_D}{N_0}\left|h_{R_m,D}\right|^2} \tag{10}$$

$$\frac{1}{\gamma_{SmD}} = \frac{1}{\frac{P_R}{N_0} \cdot \frac{P_S}{P_R + P_D} \cdot \left|h_{S,R_m}\right|^2} + \frac{1}{\frac{P_R}{N_0} \cdot \left|h_{R_m,D}\right|^2} + \frac{1}{\frac{P_R}{N_0}\left|h_{R_m,D}\right|^2 \frac{P_S}{N_0}\left|h_{S,R_m}\right|^2}. \tag{11}$$

At the high SNR region, $\frac{P_R}{N_0}\left|h_{S,R_m}\right|^2 \frac{P_D}{N_0}\left|h_{R_m,D}\right|^2 >> 1$ and $\frac{P_R}{N_0}\left|h_{R_m,D}\right|^2 \frac{P_S}{N_0}\left|h_{S,R_m}\right|^2 >> 1$ for (10) and (11) are satisfied, respectively, so we have

$$\frac{1}{\gamma_{DmS}} \approx \frac{1}{\frac{P_R}{N_0} \cdot \frac{P_D}{P_R + P_S} \cdot \left|h_{R_m,D}\right|^2} + \frac{1}{\frac{P_R}{N_0} \cdot \left|h_{S,R_m}\right|^2} \geq \max\left\{\frac{1}{\frac{P_R}{N_0} \cdot \frac{P_D}{P_R + P_S} \cdot \left|h_{R_m,D}\right|^2}, \frac{1}{\frac{P_R}{N_0} \cdot \left|h_{S,R_m}\right|^2}\right\} \tag{12}$$

$$\frac{1}{\gamma_{SmD}} \approx \frac{1}{\frac{P_R}{N_0}\cdot\frac{P_S}{P_R+P_D}\cdot\left|h_{S,R_m}\right|^2} + \frac{1}{\frac{P_R}{N_0}\cdot\left|h_{R_m,D}\right|^2} \ge \max\left\{\frac{1}{\frac{P_R}{N_0}\cdot\frac{P_S}{P_R+P_D}\cdot\left|h_{S,R_m}\right|^2}, \frac{1}{\frac{P_R}{N_0}\cdot\left|h_{R_m,D}\right|^2}\right\}. \tag{13}$$

Taking the reciprocal of (12) and (13) on both sides, the tight upper bound of γ_{DmS} and γ_{SmD} are given, respectively, by

$$\gamma_{DmS} \le \frac{P_R}{N_0}\min\{\frac{P_D}{P_R+P_S}\left|h_{R_m,D}\right|^2, \left|h_{S,R_m}\right|^2\} \tag{14}$$

$$\gamma_{SmD} \le \frac{P_R}{N_0}\min\{\frac{P_S}{P_R+P_D}\left|h_{S,R_m}\right|^2, \left|h_{R_m,D}\right|^2\}. \tag{15}$$

Substituting (14) and (15) into (9), and considering that the N^{th} best relay has to be selected, then the proposed N^{th} best relay selection scheme can be represented as:

$$m* = \arg \underset{m\in\{0,1,\dots,M-1\}}{N^{th}\max}\{\frac{P_R}{N_0}\min\{\psi\left|h_{R_m,D}\right|^2, \phi\left|h_{S,R_m}\right|^2\}\} \tag{16}$$

where $\psi = \min\{P_D/(P_R+P_S),1\}$, $\phi = \min\{P_S/(P_R+P_D),1\}$, and the argument expression $\arg \underset{m\in\{0,1,\dots,M-1\}}{N^{th}\max}\{F(m)\}$ denotes a value of the argument m, from the set $\{0,1,\dots,M-1\}$, who make the function $F(m)$ to attain its N^{th} largest value.

Observing from (16), the proposed N^{th} best-relay selection is mainly based on the channel gains $\left|h_{R_m,D}\right|$ and $\left|h_{S,R_m}\right|$, which can be implemented easily in practice, by extending the distributed timer technique in [13]. Specifically, each source node broadcasts one pilot to the relay nodes, so that relays can estimate the channel quality. Then each relay starts a timer, whose duration is inversely proportional to its estimated channel quality. The relay node, whose timer is expired, notifies the other relays via a flag packet. There is a one-bit message in the flag packet, to demonstrate the relay is busy or idle. Once N flag signals are sent, the last relay that sends the flag signal is the N^{th} best relay, denoted as R_{m*}, and the other relays keep silent. Note that a practical method to choose N is to adopt the number of the relay, who first sends the idle message.

3. Outage Probability Analysis under Outdated CSI

3.1 Outdated CSI Model

In the paper, we assume that the CSI in the relay selection phase differs from that in the data transmission phase, while the CSI remains the same in each phase separately.

At the data transmission phase, let $\hat{h}_{S,R_m}$ denote the channel coefficients between S and R_m, and $\hat{h}_{R_m,D}$ between R_m and D. Since slowly time-varying Rayleigh fading channels are adopted, the channel coefficients $\hat{h}_{S,R_m}$ and $\hat{h}_{R_m,D}$ can be modeled as two independent first-order Gauss-Markov processes [21, 30]:

$$\begin{aligned}\hat{h}_{S,R_m} &= \sqrt{\rho_{S,R_m}}h_{S,R_m} + \sqrt{1-\rho_{S,R_m}}\xi_{S,R_m}\\ \hat{h}_{R_m,D} &= \sqrt{\rho_{R_m,D}}h_{R_m,D} + \sqrt{1-\rho_{R_m,D}}\xi_{R_m,D}\end{aligned} \tag{17}$$

where ρ_{S,R_m} and $\rho_{R_m,D}$ is the correlation coefficient to describe the impact of the outdated CSI on the $S-R_m$ and R_m-D links, respectively, ξ_{S,R_m} and $\xi_{R_m,D}$ are independent white complex Gaussian processes written as $\xi_{S,R_m} \sim CN(0, d_{S,R_m}^{-\alpha})$ and $\xi_{R_m,D} \sim CN(0, d_{R_m,D}^{-\alpha})$, respectively. It is assumed that $\rho_{S,R_m} = \rho_{R_m,D} = \rho$ in the paper. From the Jakes' model, $\rho = J_0^2(2\pi f_d \tau) \in [0,1]$, where $J_0(\cdot)$ is the zero-order Bessel function of the first kind, f_d is the Doppler frequency, τ denotes the delay between the instants of the relay selection and the data transmission.

Let $u_1 = \left|h_{S,R_m}\right|^2$ and $v_1 = \left|h_{R_m,D}\right|^2$ denote the channel gains of the $S-R_m$ and R_m-D links at the relay selection phase, respectively, while $u = \left|\hat{h}_{S,R_m}\right|^2 = \left|h_{S,R_m}(t+\tau)\right|^2$ and $v = \left|\hat{h}_{R_m,D}\right|^2 = \left|h_{R_m,D}(\mathrm{t}+\tau)\right|^2$ denote the channel gains of the two links at the data transmission phase from the selected relay, respectively.

3.2 Outage Probability Analysis

In this subsection, the outage probability of the proposed scheme with outdated CSI is discussed.

The outage event occurs when either γ_{Sm*D} or γ_{Dm*S} falls below the threshold, given by:

$$\begin{aligned} P_{out} &= \Pr[\min(\gamma_{Dm*S}, \gamma_{Sm*D}) < \gamma_{th}] \\ \geq P_{out}^{low} &= \Pr\{\frac{P_R}{N_0}[\min(\psi\left|h_{R_{m*},D}\right|^2, \phi\left|h_{S,R_{m*}}\right|^2)] < \gamma_{th}\} \\ &= 1-\Pr(\frac{P_R}{N_0}\psi\left|h_{R_{m*},D}\right|^2 > \gamma_{th})\Pr(\frac{P_R}{N_0}\phi\left|h_{S,R_{m*}}\right|^2 > \gamma_{th}) \\ &= 1-\Pr(\left|h_{R_{m*},D}\right|^2 > \frac{\gamma_{th}N_0}{P_R\psi})\Pr(\left|h_{S,R_{m*}}\right|^2 > \frac{\gamma_{th}N_0}{P_R\phi}) \end{aligned} \tag{18}$$

where the threshold $\gamma_{th} = 2^{2\upsilon} - 1$, and ν is the target rate.

In the presence of the outdated CSI, the probability density function (PDF) of the channel gain u_1 for the $S-R_{m*}$ link, at the relay selection phase, is written as [31]:

$$f_{u_1}(x) = \frac{M}{d_{S,R_m}^{-\alpha}}\binom{M-1}{N-1}\sum_{m=0}^{M-N}(-1)^m\binom{M-N}{m}e^{-\frac{x(m+N)}{d_{S,R_m}^{-\alpha}}}. \tag{19}$$

Then the PDF of u conditioned on u_1, for the $S-R_{m*}$ link at the data transmission phase, takes the following expression [31]:

$$f_{u|u_1}(x) = \frac{1}{(1-\rho_{S,R_m})d_{S,R_m}^{-\alpha}}e^{-\frac{\rho_{S,R_m}u_1+x}{(1-\rho_{S,R_m})d_{S,R_m}^{-\alpha}}}I_0\left(\frac{2\sqrt{\rho_{S,R_m}xu_1}}{(1-\rho_{S,R_m})d_{S,R_m}^{-\alpha}}\right) \tag{20}$$

where $I_0(\cdot)$ stands for the zero-order modified Bessel function of the first kind. Based on (19) and (20), the PDF of u is written as (see the Appendix for the proof)

$$f_u(x) = \int_0^\infty f_{u|u_1}(x) f_{u_1}(u_1)du_1 = \sum_{m=0}^{M-N}\frac{c_m}{\beta_m}e^{-\frac{x}{\beta_m}} \tag{21}$$

where

$$c_m = (-1)^m\frac{M}{m+N}\binom{M-1}{N-1}\binom{M-N}{m} \tag{22}$$

$$\beta_m = d_{S,R_m}^{-\alpha}\left(1-\rho_{S,R_m}+\frac{\rho_{S,R_m}}{m+N}\right). \tag{23}$$

Similarly, the PDF of the channel gain v for the $R_{m*}-D$ link, at the data transmission phase, can be obtained as

$$f_v(x)=\int_0^{\infty} f_{v|v_1}(x)\, f_{v_1}(v_1)du_1=\sum_{m=0}^{M-N}\frac{c_m}{\alpha_m}e^{-\frac{x}{\alpha_m}} \tag{24}$$

where

$$\alpha_m = d_{R_m,D}^{-\alpha}\left(1-\rho_{R_m,D}+\frac{\rho_{R_m,D}}{m+N}\right). \tag{25}$$

Substituting (21) and (24) into (18), the tight lower bound of the outage probability is given by

$$P_{out}^{low}=1-\left(\sum_{m=0}^{M-N}c_m e^{-\frac{\gamma_{th}N_0}{P_R\psi\alpha_m}}\right)\left(\sum_{m=0}^{M-N}c_m e^{-\frac{\gamma_{th}N_0}{P_R\phi\beta_m}}\right). \tag{26}$$

According to the Taylor's series approximation $\lim_{x\to 0}e^{-x}\approx 1-x$ and $\sum_{m=0}^{M-N}c_m=1$, the asymptotic expression of the outage probability at the high SNR region is represented as:

$$P_{out}\approx 1-\left(1-\sum_{m=0}^{M-N}\left(\frac{c_m\gamma_{th}N_0}{P_R\psi\alpha_m}\right)\right)\left(1-\sum_{m=0}^{M-N}\left(\frac{c_m\gamma_{th}N_0}{P_R\phi\beta_m}\right)\right)\approx\sum_{m=0}^{M-N}\left(\frac{c_m\gamma_{th}N_0}{P_R\psi\alpha_m}\right)\sum_{m=0}^{M-N}\left(\frac{c_m\gamma_{th}N_0}{P_R\phi\beta_m}\right). \tag{27}$$

Simulation results later will demonstrate the tight lower bound of the outage probabilty in (26) very closely matches with simulated ones in the whole SNR region, and the asymptotic results in (27) provide good tight approximations to the simulation ones, especially in the high SNR region.

4. Simulation Results

To evaluate the performance of the proposed scheme, some simulation results are presented in the section. The number of the relays is $M=10$, the path loss $\alpha=3$, the threshold $\gamma_{th}=0$ dB, the normalized distance $d_{S,R_m}=0.2$ and $d_{R_m,D}=0.8$. For simplicity, the equal power allocation scheme is only considered, that is, $P_S=P_D=P_R$. The Equation (17) is used as the outdated CSI model in the simulation, where the correlation coefficients are assumed as $\rho_{S,R_m}=\rho_{R_m,D}=\rho$.

Fig. 4 shows the analytical and simulated results of outage probability versus SNR, under the perfect CSI with the channel correlation coefficient $\rho=1$, in the case of $N\in\{1,2,4\}$. Note that $N=1$ is corresponding to the existing optimal relay selection scheme [29], which is a special case included in our proposed scheme. It is shown that the outage performance becomes worse as N increases, since the best relay is unavailable and the N^{th} best relay is chosen under outdated CSI. It also can be observed that the analytical results are very close to the simulated ones in the whole SNR region. Furthermore, it is worth noting that the curves have the same slopes for different values of N, since the diversity order of the two-way-relaying system is equal to the number of the relays when the CSI is perfect with $\rho=1$.

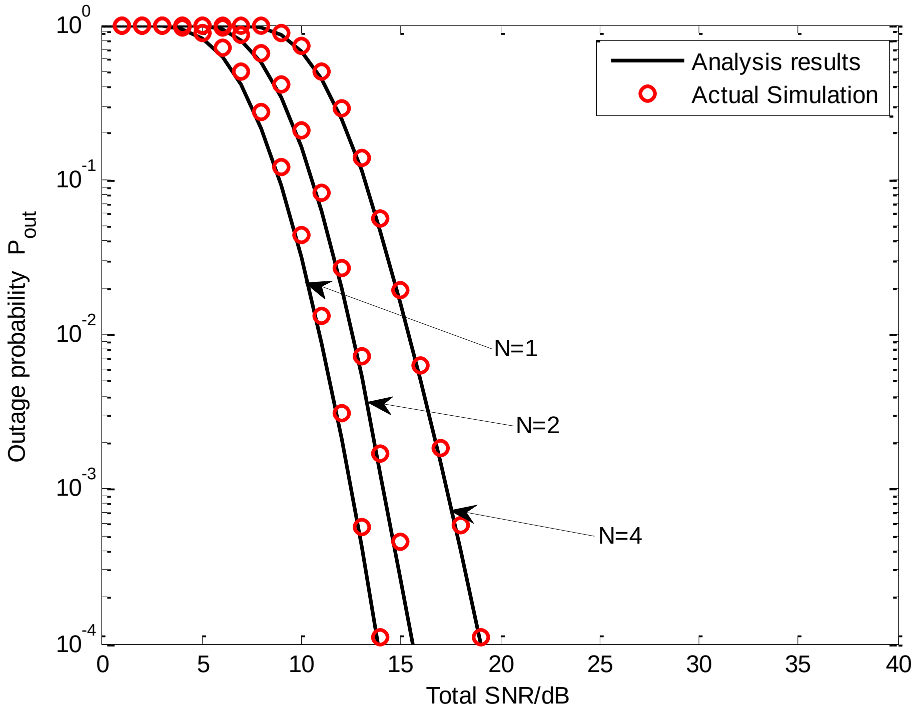

Fig. 4. Outage probability vs. total SNR, $\rho = 1$ and $N \in \{1, 2, 4\}$

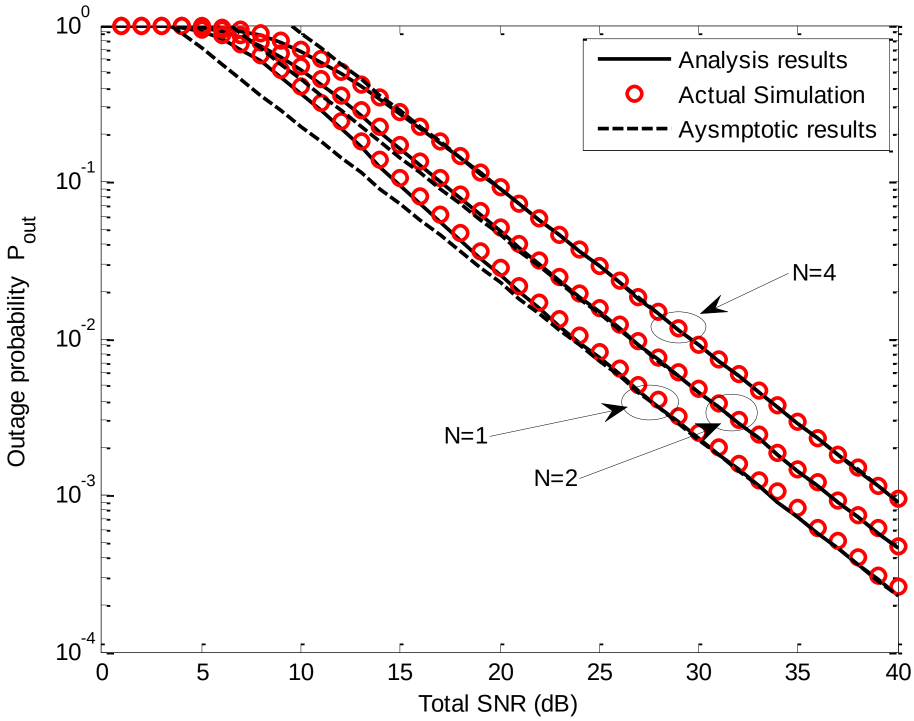

Fig. 5. Outage probability vs. total SNR, $\rho = 0.5$ and $N \in \{1, 2, 4\}$

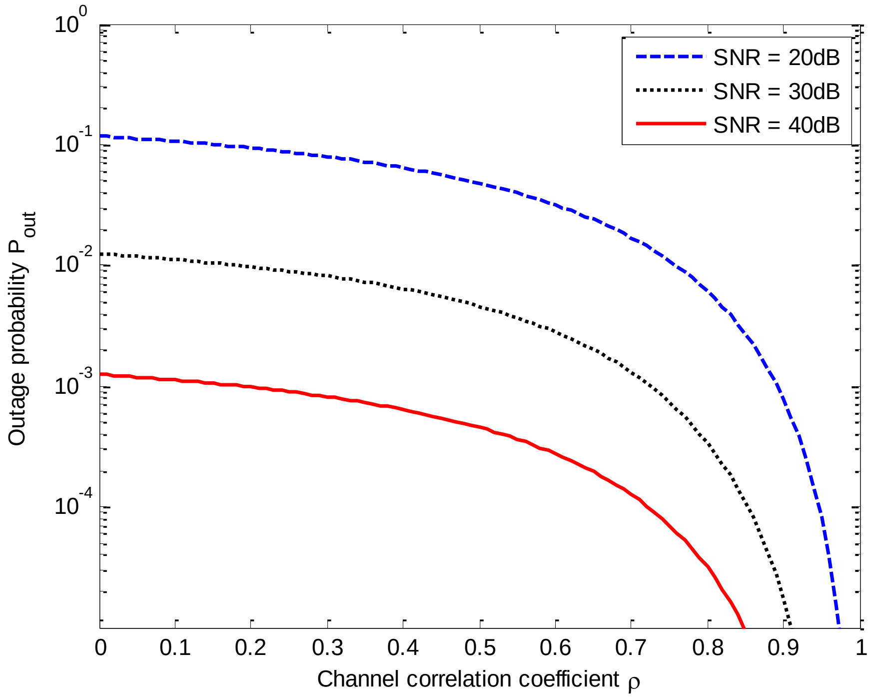

Fig. 6. Outage probability vs. ρ , SNR={20dB，30dB，40dB} and $N = 2$

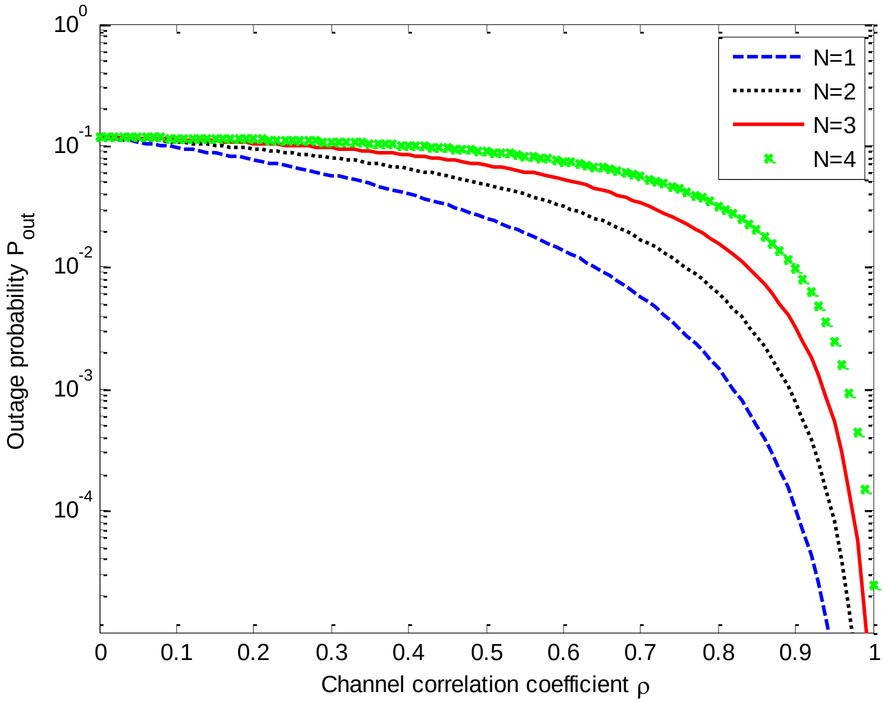

Fig. 7. Outage probability vs. ρ , $N \in \{1,2,3,4\}$ and SNR=20dB

Fig. 5 plots the analytical, asymptotic and simulated results of outage probability versus SNR, under the outdated CSI with $\rho = 0.5$, in the case of $N \in \{1, 2, 4\}$. As observed from the figure, the analytical results very closely match with simulated ones in the whole SNR region, and the asymptotic results provide good tight approximations to the simulation ones, especially in the high SNR region. It also can be found that the outage performance is worse in **Fig. 5** when $\rho = 0.5$, in comparison with that in **Fig. 4** when $\rho = 1$. Moreover, the curves have the same slopes for different values of N, since the diversity order of the opportunistic two-way-relaying system is equal to one when ρ is less than one.

In order to depict the great impact of the outdated CSI on the system performances, **Fig. 6** demonstrates the outage probability as a function of ρ, where $N = 2$ and different values SNR={20dB, 30dB, 40dB}. As expected, better results are obtained by increasing the value of ρ, since larger ρ means better quality of the channel. **Fig. 7** describes the outage probability as a function of ρ, for SNR=20dB and different values $N \in \{1, 2, 3, 4\}$. It also can be seen that the outage performance becomes better when ρ increases. For $N = 1$ as an example, the outage probability are around 10^{-3} and 10^{-4} when ρ is equal to 0.8 and 0.9, respectively. In addition, it also shows that the outage performance becomes worse when N is increased.

5. Conclusion

The opportunistic two-way relay selection, where the best relay is chosen, is one of the most efficient schemes to utilize spatial diversity. The selected best relay, however, might be unavailable due to various reasons in the real system, such as load balancing and scheduling issues. In this paper, the simple N^{th} best-relay selection scheme for the opportunistic two-way relay networks is proposed, which is mainly based on the channel gains and can be implemented easily in practice. The outage performance of the proposed scheme is discussed with the outdated CSI, and the closed-form lower bound of the outage probability and its approximation in the high SNR region are derived. Numerical and simulation results have verified the theoretical analyses. Note that the CSI among the relays is required to be considered to improve the system performance. Besides, balancing tasks that the best relays have to listen to the network to send the flag packet while they are busy with their own normal work, should also be investigated. These problems mentioned above are left for future research.

Appendix

The PDF $f_u(x)$ of the channel for the data transmission phase is obtained from the PDF $f_{u_1}(u_1)$ of the channel for the relay selection phase and the conditional PDF $f_{u|u_1}(x)$ of the channel for the data transmission phase. Hence, substituting (19) and (20) into (21), and using the fact $\int_0^\infty e^{-\alpha z} I_0\left(2\sqrt{\beta z}\right) dz = \frac{1}{\alpha} e^{\frac{\beta}{\alpha}}$ in Equation (6.614.3) in [32], yields

$$\begin{aligned}
f_u(x) &= \int_0^{\infty} f_{u|u_1}(x) f_{u_1}(u_1) du_1 \\
&= \sum_{m=0}^{M-N} (-1)^m \binom{M-1}{N-1}\binom{M-N}{m} \frac{M}{d_{S,R_m}^{-\alpha}} \frac{1}{(1-\rho_{S,R_m})d_{S,R_m}^{-\alpha}} e^{-\frac{x}{(1-\rho_{S,R_m})d_{S,R_m}^{-\alpha}}} \\
&\quad \times \int_0^{\infty} e^{-\left(\frac{(m+N)}{d_{S,R_m}^{-\alpha}}+\frac{\rho_{S,R_m}}{(1-\rho_{S,R_m})d_{S,R_m}^{-\alpha}}\right)u_1} I_0\left(\frac{2\sqrt{\rho_{S,R_m} x u_1}}{(1-\rho_{S,R_m})d_{S,R_m}^{-\alpha}}\right) du_1 \\
&= \sum_{m=0}^{M-N} (-1)^m \frac{M}{m+N} \binom{M-1}{N-1}\binom{M-N}{m} \frac{1}{d_{S,R_m}^{-\alpha}[1-\rho_{S,R_m}+\frac{\rho_{S,R_m}}{m+N}]} e^{\frac{-x}{d_{S,R_m}^{-\alpha}[1-\rho_{S,R_m}+\frac{\rho_{S,R_m}}{m+N}]}} \\
&= \sum_{m=0}^{M-N} \frac{c_m}{\beta_m} e^{-\frac{x}{\beta_m}}
\end{aligned}$$

where $c_m = (-1)^m \frac{M}{m+N}\binom{M-1}{N-1}\binom{M-N}{m}$, $\beta_m = d_{S,R_m}^{-\alpha}\left(1-\rho_{S,R_m}+\frac{\rho_{S,R_m}}{m+N}\right)$.

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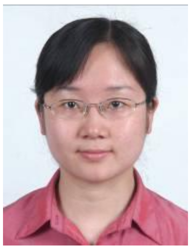

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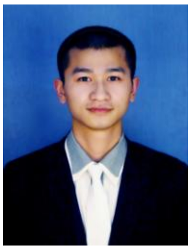

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