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RESEARCH

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Performance analysis of two-way full-duplex relay with antenna selection under Nakagami channels

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Abstract

This paper focuses on a full-duplex (FD) two-way relay network with one base station (BS), one FD amplify-and-forward (AF) relay, and one user, and the BS is equipped with massive multiple-input multiple-output (MIMO) antennas. To reduce the complexity and cost of BS, the paper proposes a practical antenna selection way in BS to complete transmission in two-way FD relay networks to optimize the system performance of outage probability or bit error ratio (BER). In the proposed scheme, BS can implement transmit antenna selection (AS) based on the instantaneous channel state information (CSI), thereby improving the system performance compared to the traditional FD relay networks. Furthermore, closed-form expressions for the outage probability and average BER are derived under Nakagami-*m* channels. The analytical results show that the superiority of proposed scheme compared with the conventional AF relay scheme and the correctness of the theoretical analysis verified by the Monte Carlo simulations.

Keywords: Full-duplex relay, Amplify-and-forward relay, Antenna selection, Outage probability, Bit error rate

1 Introduction

MIMO has been adopted by various wireless standards, such as Third Generation Partnership Project (3GPP), long-term evolution (LTE), and 5G communications, as a promising way to boost system throughput and improve coverage range. Massive MIMO systems employing simple linear precoding and combining schemes can offer significant performance gains in terms of bandwidth, power, and energy efficiency compared to conventional multiuser MIMO systems, as impairments such as fading, noise, and interference are averaged out for very large numbers of base station (BS) antennas. Antenna diversity is one of the most effective techniques to combat the multipath fading and shadowing in wireless communications [1–3]. However, each additional antenna comes along with an additional radio frequency (RF) chain and power consumption, which may increase the transmission cost and complexity of the system as a whole. A remedy for this crucial issue is the use of antenna selection, which can reduce system cost and complexity and improve the system error performance considerably through selecting a single antenna or a group of antennas [4–8].

Relay technologies are also included in the current standard for wireless metropolitan area networks such as IEEE 802.16j and IEEE 802.16 m and are adopted by cellular communication systems such as 3GPP and LTE-Advanced [9, 10]. There has been lots of research on antenna selection in AF relay networks recently [11–15]. In another study, Zheng provided a semi-analytical result on the error performance of the fractionally spaced frequency domain and minimum mean square error receiver over flat Nakagami-*m* fading channels and derived the bit error rate (BER) and outage probability [16]. You and co-authors proposed dual antenna selection strategies for MIMO scenarios with partial feedback based on system outage probability minimization and sum rate maximization of two-way MIMO AF relay networks [17–19]. Some authors also investigated the beamforming schemes and interference alignment in cognitive networks [20, 21].

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In more recent years, one-way DF relay considered with AS has also garnered a great deal of research interest. Lv and co-author investigated the max-min method for relay AS in two-way DF relay systems and proposed a single antenna system with receiver optimization [22, 23]. Their approach can be implemented in a distributed manner without acquiring full channel state information (CSI) at the relay node. Meanwhile, some authors also investigate other key technologies about 5G except the full-duplex system [24–27].

For conventional bidirectional communications, most researchers to date have focused primarily on half-duplex (HD) relay. Recently, with the advent of multi-antenna technologies, there has been a renewed interest in the use of the FD relay [28, 29]. In one such study, Krikidis proposed an optimal relay selection procedure that incorporates a hybrid relaying strategy which dynamically switches between FD and HD relaying according to the instantaneous channel conditions [28]; this system well outperformed the conventional FD relay system. In another study, Riihonen attempted to maximize the D2D information rate from the source to the destination for the FD-AF relay with multiple antennas of transmitter and receiver [29]. The optimal transformation matrix of the relay was derived under the assumption that the self-interference is perfectly canceled by time domain digital signal processing.

The remainder of the paper is organized as follows. First, in Section 2, we elaborate the research methods and contributions in the paper. Section 3 describes the system model. Then, we propose the max-min antenna selection scheme in Section 4. In Section 4, we derive the performance of antenna selection for two-way FD-AF relay networks in the flat Nakagami-m fading channel. Simulation results are given in Section 5, and Section 6 concludes the paper.

2 Methods/experimental

There has been very extensive research on FD relay in 5G networks. Merra et al. analyzed the multiband cognitive radio full-duplex relay and obtained the outage probability expressions [30]. Zhang et al. explored the performance of light communication networks with full-duplex optical links and proposed two contention protocols to utilize the FD capability effectively [31]. Atzeni used stochastic geometry to analyze the performance of wireless networks with FD multi-antenna small cells and emphasis on the probability of successful transmission [32]. It is important to note that all of these studies explored transmission protocol and performance through stochastic geometry; performance analyses on the two-way FD-AF relay with antenna selection in 5G systems are, at present, few and far between. This paper emphasizes this perspective from which we attempted to achieve outage probability and BER expressions.

The full-duplex system can achieve two times the spectrum gains of the half duplex. However, how does the performance of the FD relay system fare in terms of antenna selection? To the best of our knowledge, performance analyses of two-way FD-AF relay networks in terms of antenna selection are scarce in recent studies. The performance analysis of massive MIMO combined with antenna selection in the FD relay network was derived in this study with various channel models. In our previous work, we have investigate the performance of antenna selection with AF and DF half-duplex relay networks [3], our main contributions in this paper can be summarized as follows.

1) We propose an antenna selection scheme for FD-AF relay networks based on the max-min criterion.
2) We derived the closed-form outage probability and BER expressions in flat Nakagami-m fading channels. Our analysis shows that the proposed scheme achieves superior performance compared to other conventional schemes.

3 System model

We consider two-way FD-AF relay networks as shown in Fig. 1, where S_1, R, and S_2 are equipped with N_1, N_R, and N_2 antennas, respectively. $\mathbf{H}$ and $\mathbf{G}$ are channel matrix of links $S_1 \rightarrow R$ and $S_2 \rightarrow R$, respectively. We assume all elements of $\mathbf{H}$ and $\mathbf{G}$ are independent and identically distributed (i.i.d.) flat Nakagami-m fading. It is worth noting that the Nakagami-m fading is a general case, which can cover Rayleigh fading or Rician fading and so on, such as $m = 1$ means Nakagami-m is equal to Rayleigh fading. There is no direct link between S_1 and S_2, and all nodes are working in a full-duplex mode. Based on known CSI, the BS select one of their antennas separately for transmission. The work process of the two-way FD-AF relay networks can be seen as follows.

The relay always amplifies and forwards the received signal in every time slot because of its full-duplex mode.

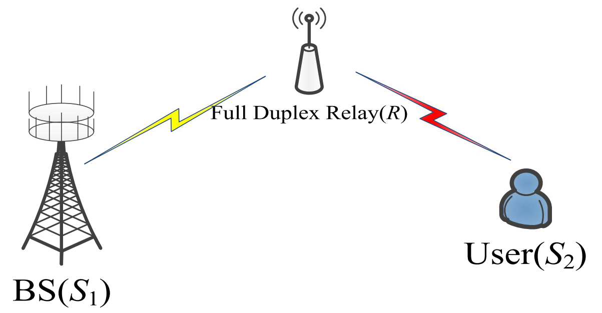

Fig. 1 The system model

Therefore, we denote n as time slot number. In nth time slot, the BS S_1 and user S_2 send their information $x_1[n]$ and $x_2[n]$ simultaneously, then the relay node R amplifies and forwards the received signal in the $(n+1)$th time slot. In time slot n, BS selects the ith antenna through the max-min criterion in the following, then the received signal in relay R can be expressed as follows:

$$y_R[n] = \sqrt{P_1} h_i x_1[n] + \sqrt{P_2} g x_2[n] + \sqrt{P^{(R)}} h^{(R)} t[n] + n_R[n] \tag{1}$$

where h_i is the ith column of $\mathbf{h}$, $t[n]$ is the forward signal, and n_R is additive Gaussian white noise of R and satisfies $n_R \sim \mathcal{CN}(0, \sigma_R^2)$, where $\mathcal{CN}(\mu, \sigma^2)$ represents circular symmetric complex Gaussian distribution of μ mean and σ^2 variance.

For the full-duplex relay network, the forward signal $t[n]$ is determined by the received signal $y_R[n-1]$. Due to the power constraint of the relay node, the received signal y_R then needs to multiply factor α as follows:

$$\alpha = \sqrt{\frac{1}{P_1 \|h_i\|^2 + P_2 \|g\|^2 + P^{(R)} \left\|h^{(R)}\right\|^2 + \sigma_R^2}} \tag{2}$$

In the nth time slot, R sends the amplified signal $\alpha y_R[n]$.

Based on the channel reciprocity in the TDD (time division duplex) system, the signal in nth time slot can be rewritten as follows:

$$\begin{aligned} y_1[n] &= \sqrt{P_R} \alpha h_i^* y_R[n-1] + \sqrt{P^{(1)}} h_i^{(1)} x_1[n] + n_1[n] \\ y_2[n] &= \sqrt{P_R} \alpha g^* y_R[n-1] + \sqrt{P^{(2)}} h_i^{(2)} x_2[n] + n_2[n] \end{aligned} \tag{3}$$

where $(\cdot)^*$ stands for the conjugate transpose and n_1 and n_2 represent the additive white Gaussian noise for B and U, respectively, and satisfy $n_1 \sim \mathcal{CN}(0, \sigma_1^2)$ and $n_2 \sim \mathcal{CN}(0, \sigma_2^2)$.

After self-cancelation for B and U, the equivalent signal can be expressed as follows:

$$\begin{aligned} \tilde{y}_1[n] &= \sqrt{P_R P_2} \alpha h_i^* g x_2[n] + \sqrt{P_R P^{(R)}} \alpha h_i^* h^{(R)} t[n] \\ &+ \sqrt{P_R} \alpha h_i^* n_R[n] + \sqrt{P^{(1)}} h_i^{(1)} x_1[n] + n_1[n] \\ \tilde{y}_2[n] &= \sqrt{P_R P_1} \alpha g^* h_i x_1[n] + \sqrt{P_R P^{(R)}} \alpha g^* h^{(R)} t[n] \\ &+ \sqrt{P_R} \alpha g^* n_R[n] + \sqrt{P^{(2)}} h^{(2)} x_2[n] + n_2[n] \end{aligned} \tag{4}$$

Without loss of generality, we assume $\sigma_R^2 = \sigma_1^2 = \sigma_2^2 = 1$ and the self-interference channel of each node varies slowly relative to the transceiver channel. The SNR of B and U can be obtained as follows:

$$\begin{aligned} \gamma_1 &= \frac{\tilde{P}_2 \tilde{P}_R^{(1)} \|h_i\|^2 \|g\|^2}{\left(\tilde{P}_R^{(1)} + \tilde{P}_1\right) \|h_i\|^2 + \tilde{P}_2 \|g\|^2 + 1} \\ \gamma_2 &= \frac{\tilde{P}_1 \tilde{P}_R^{(2)} \|h_i\|^2 \|g\|^2}{\tilde{P}_1 \|h_i\|^2 + \left(\tilde{P}_R^{(2)} + \tilde{P}_2\right) \|g\|^2 + 1} \end{aligned} \tag{5}$$

where

$$\tilde{P}_1 = \frac{P_1}{P^{(R)} \left(\sigma^{(R)}\right)^2 + 1}$$

$$\tilde{P}_2 = \frac{P_2}{P^{(R)} \left(\sigma^{(R)}\right)^2 + 1}$$

$$\tilde{P}_R^{(1)} = \frac{P_R}{P^{(1)} \left(\sigma_i^{(1)}\right)^2 + 1}$$

$$\tilde{P}_R^{(2)} = \frac{P_R}{P^{(2)} \left(\sigma_k^{(2)}\right)^2 + 1}$$

The corresponding channel variance can be defined as $\left(\sigma_j^{(R)}\right)^2 = E\{\|h^{(R)}\|^2\}$, $\left(\sigma_i^{(1)}\right)^2 = E\{\|h_i^{(1)}\|^2\}$, and $\left(\sigma_k^{(2)}\right)^2 = E\{\|h^{(2)}\|^2\}$, where $E\{\cdot\}$ represents random variable expectation operation.

The BS works under an optimal antenna selection scheme where the optimal antenna as selected can be used to transmit and receive signals. The selection criterion can be expressed as follows:

$$\widehat{i} = \arg \max_i \min\{\gamma_1, \gamma_2\} \tag{6}$$

The selection criterion can be modified as follows via some mathematical manipulation:

$$\widehat{i} = \arg \max_i \|h_i\|^2 \tag{7}$$

It is worth noting that the value of $\|h_i\|^2$may be very large when massive MIMO BS includes optimal antenna selection. Therefore, $\gamma_1$and γ_2 can be approximated as:

$$\begin{aligned} \gamma_1 &\approx \frac{\tilde{P}_2 \tilde{P}_R^{(1)} \|h_i\|^2 \|g\|^2}{\left(\tilde{P}_R^{(1)} + P_1\right) \|h_i\|^2 + \tilde{P}_2 \|g\|^2} \\ \gamma_2 &\approx \frac{\tilde{P}_1 \tilde{P}_R^{(2)} \|h_i\|^2 \|g\|^2}{\tilde{P}_1 \|h_i\|^2 + \left(\tilde{P}_R^{(2)} + \tilde{P}_2\right) \|g\|^2} \end{aligned} \tag{8}$$

4 Performance analysis

4.1 PDF of end-to-end SNR

In this section, we derive probability density function (PDF) in high SNR approximation based on end-to-end SNR analysis and outage probability. We assume that

$\|h_i\|^2 \sim \mathcal{CN}(0, \sigma_h^2)$ and $\|g\|^2 \sim Gamma(\alpha, \beta)$, then the PDF of $\|h_i\|^2$ and $\|g\|^2$ can be expressed as [33]:

$$f_{\|h_i\|^2}(x) = \frac{1}{\sigma_h^2} e^{-\frac{x}{\sigma_h^2}} \tag{9}$$

$$f_{\|g\|^2}(y) = \frac{\beta^\alpha}{\Gamma(\alpha)} y^{\alpha-1} e^{-\beta y} \tag{10}$$

It is worth noting that channel g follows Nakagami channel, and its norm square obeys the Gamma distribution. Nakagami-m channel can be equivalent to other wireless multipath fading channels with different parameters $m \in (\frac{1}{2}, \infty)$, which present that Nakagami-m channel can cover other fading channels generally. In other words, Nakagami channel model has become a general channel model and thus has a high application value such as

$$\text{Nakagami-}m\text{ channel} = \begin{cases} \text{Unilateral Gaussian channel}, & m = \frac{1}{2} \\ \text{Rayleigh channel}, & m = 1 \\ \text{Nagami-}n, m = \frac{(1+n^2)^2}{1+2n^2}, & n \geq 0 \\ \text{Rice channel}, K = n^2 = \frac{\sqrt{m^2 - m}}{m - \sqrt{m^2 - m}}, & m \geq 1 \\ \text{Constant channel}, & m = \infty \end{cases}$$

The BS can achieve optimal antenna selection after finishing the antenna selection scheme. The PDF and CDF of equivalent channel $\|h\|^2 = \max_i \|h_i\|^2$ can then be expressed as:

$$f_{\|h\|^2}(x) = \frac{N_B}{\sigma_h^2} \left(1 - e^{-\frac{x}{\sigma_h^2}}\right)^{N_B - 1} e^{-\frac{x}{\sigma_h^2}} \tag{11}$$

$$F_{\|h\|^2}(x) = \left(1 - e^{-\frac{x}{\sigma_h^2}}\right)^{N_B} \tag{12}$$

Because channels h and g are independent, then the joint probability density function of h and g can be calculated as follows:

$$p_{\|h\|^2, \|g\|^2}(x, y) = \frac{N_B}{\sigma_h^2} \cdot \frac{\beta^\alpha}{\Gamma(\alpha)} \left(1 - e^{-\frac{x}{\sigma_h^2}}\right)^{N_B - 1} \cdot e^{-\frac{x}{\sigma_h^2}} \cdot y^{\alpha - 1} \cdot e^{-\beta y} \tag{13}$$

We can define two new variables to derive the PDF of γ_1 and γ_2.

We can define $z = \frac{xy}{ax+by}$, $\omega = \frac{ax^2}{ax+by}$. The Jacobian determinant can then be expressed as follows [34]:

$$\det(J_F(z, \omega)) = \det \begin{bmatrix} \frac{\partial x}{\partial z} & \frac{\partial x}{\partial \omega} \\ \frac{\partial y}{\partial z} & \frac{\partial y}{\partial \omega} \end{bmatrix} = a + \frac{2abz}{\omega} + \frac{ab^2 z^2}{\omega^2} \tag{14}$$

where the joint PDF of Z and W is:

$$p_{Z,W}(z, \omega) = \det(J_F(z, \omega)) \frac{N_B}{\sigma_h^2} \cdot \frac{\beta^\alpha}{\Gamma(\alpha)} \cdot \sum_{j=0}^{N_B - 1} C_{N_B - 1}^j (-1)^j \left[az + \frac{abz^2}{\omega}\right]^{\alpha - 1} \cdot e^{-\frac{j+1}{\sigma_h^2}(\omega + bz)} \cdot e^{-\beta\left[az + \frac{abz^2}{\omega}\right]} \tag{15}$$

then we can derive the PDF of Z as:

$$p_Z(z) = \int_0^\infty p_{ZW}(z, \omega) d\omega \tag{16}$$

Substitute the joint PDF $p_{ZW}(z, \omega)$ to the integral of $p_Z(z)$:

$$p_Z(z) = \int_0^\infty \frac{N_B}{\sigma_h^2} \cdot \frac{\beta^\alpha}{\Gamma(\alpha)} \cdot \sum_{j=0}^{N_B - 1} (-1)^j \cdot \left[a + \frac{2abz}{\omega} + \frac{ab^2 z^2}{\omega^2}\right] \cdot \left[az + \frac{abz^2}{\omega}\right]^{\alpha - 1} \cdot e^{-\frac{j+1}{\sigma_h^2} \cdot (\omega + bz)} \cdot e^{-\beta\left[az + \frac{abz^2}{\omega}\right]} d\omega \tag{17}$$

Then, the integral of $p_Z(z)$ can be divided into three parts:

$$p_Z(z) = \frac{N_B}{\sigma_h^2} \cdot \frac{\beta^\alpha}{\Gamma(\alpha)} \cdot \int_0^\infty (I_1 + I_2 + I_3) d\omega \tag{18}$$

where I1, I2, and I3 can be represented as follows:

$$I_1 = a \cdot \left[az + \frac{abz^2}{\omega}\right]^{\alpha - 1} \cdot e^{-\frac{j+1}{\sigma_h^2} \cdot (\omega + bz)} \cdot e^{-\beta\left[az + \frac{abz^2}{\omega}\right]} \tag{19}$$

$$I_2 = \frac{2abz}{\omega} \cdot \left[az + \frac{abz^2}{\omega}\right]^{\alpha - 1} \cdot e^{-\frac{j+1}{\sigma_h^2} \cdot (\omega + bz)} \cdot e^{-\beta\left[az + \frac{abz^2}{\omega}\right]} \tag{20}$$

$$I_3 = \frac{ab^2 z^2}{\omega^2} \cdot \left[az + \frac{abz^2}{\omega}\right]^{\alpha - 1} \cdot e^{-\frac{j+1}{\sigma_h^2} \cdot (\omega + bz)} \cdot e^{-\beta\left[az + \frac{abz^2}{\omega}\right]} \tag{21}$$

Therefore, we can determine the PDF of $z = \frac{xy}{ax+by}$ as:

$$p_Z(z)=\frac{N_B}{\sigma_h^2}\cdot\frac{\beta^\alpha}{\Gamma(\alpha)}\cdot\sum_{j=0}^{N_B-1}\sum_{k=0}^{\alpha-1}C_{N_B-1}^{j}C_{\alpha-1}^{k}(-1)^j$$
$$\cdot\left(\frac{j+1}{\sigma_h^2}\right)^{\frac{k}{2}}\cdot e^{-\left[\frac{j+1}{\sigma_h^2}b+\beta a\right]z}\cdot\beta^{\frac{-k}{2}}\cdot a^{\alpha-\frac{k}{2}}\cdot b^{\frac{k}{2}}\cdot z^\alpha\cdot$$
$$\left\{\left(\frac{j+1}{\sigma_h^2}\cdot\frac{b}{\beta a}\right)^{-\frac{1}{2}}2z^{-1}K_{k-1}\left(2z\sqrt{\beta ab\frac{j+1}{\sigma_h^2}}\right)+4bK_k\left(2z\sqrt{\beta ab\frac{j+1}{\sigma_h^2}}\right)\right.$$
$$\left.+\left(\frac{j+1}{\sigma_h^2}\cdot\frac{1}{\beta a}\right)^{\frac{1}{2}}b^{\frac{3}{2}}2z^{-2}K_{k+1}\left(2z\sqrt{\beta ab\frac{j+1}{\sigma_h^2}}\right)\right\} \tag{22}$$

where the special function $K_\alpha(x)$ of PDF is modified Bessel function, the Bessel functions are valid even for complex arguments x, and an important special case is that of a purely imaginary argument. In this case, the solutions to the Bessel equation are called the modified Bessel functions of the second kind. It is worth noting that the parameter α in the special function $K_\alpha(x)$ is not an integer, when α is an integer, then the limit is used, these are chosen to be real-valued for real and positive arguments x.

4.2 Outage probability

As established by the researchers referenced above, any link SNR lower than the threshold can result in system outage. The outage probability of the system model can be expressed as:

$$\begin{aligned}P_{\text{out}}=&\ \Pr\{\min(\gamma_1,\gamma_2)<\gamma_{\text{th}}\}\\=&\ 1-\left(1-P_{\gamma_1}(\gamma_{\text{th}})\right)\left(1-P_{\gamma_2}(\gamma_{\text{th}})\right)\end{aligned} \tag{23}$$

where $P_{\gamma_1}(x)$ and $P_{\gamma_2}(x)$ represent the cumulative distribution function (CDF) of two end nodes' SNR.

The CDF of $P_{\gamma_1}(x)$ and $P_{\gamma_2}(x)$ can be obtained based on the derived PDF; however, the expressions of $P_{\gamma_1}(x)$ and $P_{\gamma_2}(x)$ are complex. We can achieve the approximation expression of P_{out}using the relationship between system outage probability and parameters:

$$P_{\text{out}}=1-\left[1-\left(1-e^{-\frac{\gamma_{\text{th}}}{\tilde{\Omega}_1}}\right)^{N_B}\right]\cdot\frac{\Gamma(\alpha,\beta\gamma_{\text{th}})}{\Gamma(\alpha)} \tag{24}$$

where $\tilde{\Omega}_1=\frac{\tilde{P}_R\tilde{P}_2}{\tilde{P}_R+\tilde{P}_1}\theta_1$.

The BS antenna number is greater than users' in massive MIMO system, so we can obtain the following corollary:

Corollary 1 *When the BS antenna number is larger than users'* ($N_B>>1$), *then the outage probability can be approximated as follows:*

$$P_{\text{out}}\approx 1-\frac{\Gamma(\alpha,\beta\gamma_{\text{th}})}{\Gamma(\alpha)} \tag{25}$$

It can be elaborated the proof process in a simple mode, when $N_B>>1$, then $1-e^{-\frac{\gamma_{\text{th}}}{\tilde{\Omega}_1}}<1$, we can obtain

$$\lim_{N_B\to\infty}\left(1-e^{-\frac{\gamma_{\text{th}}}{\tilde{\Omega}_1}}\right)^{N_B}=0$$

Then, the corollary can be achieved normally.

It is worth noting that the outage probability of a massive MIMO full-duplex system is limited to the link between relay and user, the reason being that the link between the BS and relay tends to be idealized when the BS antenna number grows to infinity. The link quality between relay and user shows unobvious improvement, however.

4.3 Average BER

It is known that the average BER can be defined as the average level of each link BER. We assume that P_1 is the BER of link $B\to R\to U$ and P_2 is the BER of link $U\to R\to B$. The average BER is decided by the worst link BER. We can then rewrite P_e as follows:

$$P_e\approx\frac{1}{2}\max(P_1,P_2) \tag{26}$$

Theorem 2 *The average BER of the optimal antenna selection scheme can be expressed as:*

$$\begin{aligned}P_e\approx&\ \frac{1}{2}\max(P_1,P_2)\\=&\ \frac{t_1\sqrt{t_2}}{4\sqrt{\pi}}\frac{\beta^\alpha\Gamma\left(\alpha+\frac{1}{2}\right)}{(\beta+t_2)^{\alpha+\frac{1}{2}}\Gamma(\alpha+1)}{}_2F_1\left(1,\alpha+\frac{1}{2};\alpha+1;\frac{\beta}{\beta+t_2}\right)\\&+\frac{t_1\sqrt{t_2}}{4\sqrt{\pi}}\sum_{i=0}^{N_B}C_{N_B}^{i}(-1)^i\frac{2\beta^\alpha\Gamma\left(\alpha+\frac{1}{2}\right)}{\left(\beta+t_2+\frac{i}{\tilde{\Omega}_1}\right)^{\alpha+\frac{1}{2}}\Gamma(\alpha)}{}_2F_1\left(1,\alpha+\frac{1}{2};\frac{3}{2};\frac{t_2+\frac{i}{\tilde{\Omega}_1}}{\beta+t_2+\frac{i}{\tilde{\Omega}_1}}\right)\end{aligned} \tag{27}$$

The proof can be seen as Appendix. Where the special function ${}_2F_1(a,b;c;z)$ in the P_e is the hypergeometric function, the Gaussian or ordinary hypergeometric function ${}_2F_1(a,b;c;z)$ is a special function represented by the hypergeometric series, that includes many other special functions as specific or limiting cases. It is a solution of a second-order linear ordinary differential equation and can be defined as ${}_2F_1(a,b;c;z)=\sum_{n=0}^{\infty}\frac{(a)_n(b)_n}{(c)_n}\frac{z^n}{n!}$.

Therefore, this section derived the full-duplex two-way relay system end node's SNR PDF. On the basis of this derivation, we further investigated the system outage probability and asymptotic BER expressions as discussed below.

5 Results and discussion

This section focuses on verifying the effectiveness of the proposed scheme and the correctness of said performance analysis as well as the discussion of the results.

The outage probability and BER of the two-way FD-AF relay network with antenna selection were simulated and analyzed in detail. The simulation scenario is depicted in Fig. 1, where the FD-AF relay network consists of BS, relay, and user; BS is equipped with a massive antenna and the relay and user have single antennas. It is assumed that the channel between BS and relay follows Rayleigh fading, and the channel between relay and user follows Nakagami-m fading. The simulation target is to select one antenna from the BS to complete transmission and verify the correctness of our theoretical analysis. As shown in Fig. 1, the parameter β increasing can bring about the improvement of the system performance, because the parameter β represents the strength of line-of-sight.

Figure 2 plots the PDF of end-to-end SNR results of the FD-AF relay network, where $\beta = \alpha/\tilde{\Omega}_1 = 1, 2$ represents the line of sight level of direct link, $(\sigma^{(R)})^2 = (\sigma^{(1)})^2 = (\sigma^{(2)})^2 = 0.1$. As shown in Fig. 2, the proposed approximation method is effective when BS antenna number is high. Moreover, β has a certain influence on the approximation result: The gap between analytical results and simulation reduces gradually as BS antenna number and β increase. The parameter β represents the line of sight between transmitter and receiver; therefore, the parameter β is bigger and the system performance is better.

Figure 3 compares the system outage probability tendency with different parameters, where outage threshold $R_0 = 1\text{bit}/s/Hz$. As shown in Fig. 3, the asymptotic curves drawn via Eq. (25) approach the simulation result as BS antenna number grows. Moreover, the system outage probability decreases as SNR increases, as well as β, the reason being that β represents the line of sight level with fixed $\tilde{\Omega}_i(i = 1, 2)$, so SNR or β augment may result in an equivalent increase in SNR at the receiver.

Figure 4 shows the analytical results alongside the Monte Carlo simulations, which demonstrate the correctness of our outage probability analysis. We also found that insofar as the system outage probability is almost equivalent to the worst link outage probability, it is similar to the “bucket effect” in practice.

Figure 5 displays the tendency of asymptotic, analytical, and simulation system outage probability results as SNR increases. In particular, Fig. 5 reveals that the system outage probability curves coincide with increase in BS antennas; in effect, high SNR or transmit power has significant impact on the outage probability and other system performance factors. It is worth noting that system outage

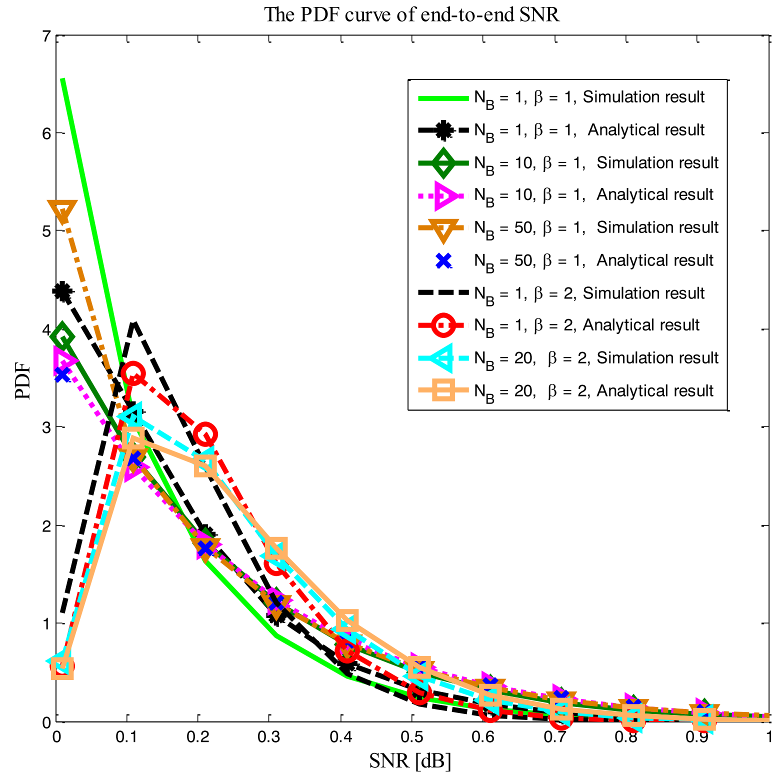

Fig. 2 The PDF curve of end-to-end SNR

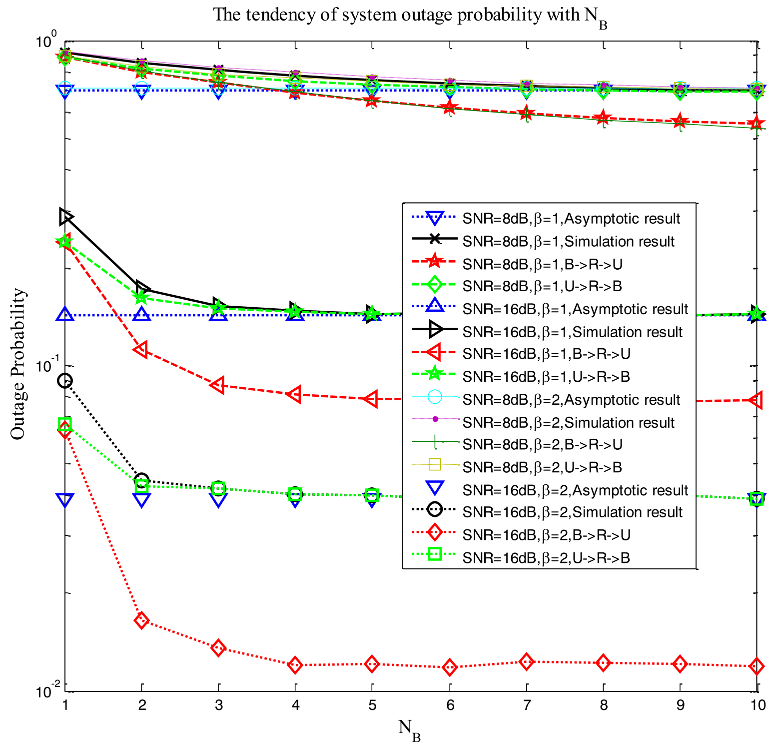

Fig. 3 The tendency of system outage probability with N_B

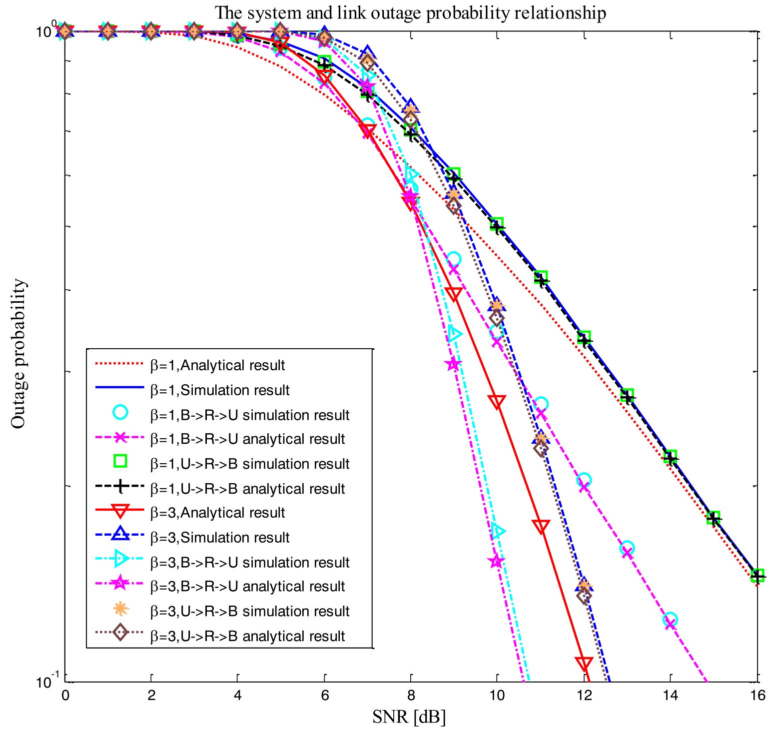

Fig. 4 The system and link outage probability relationship

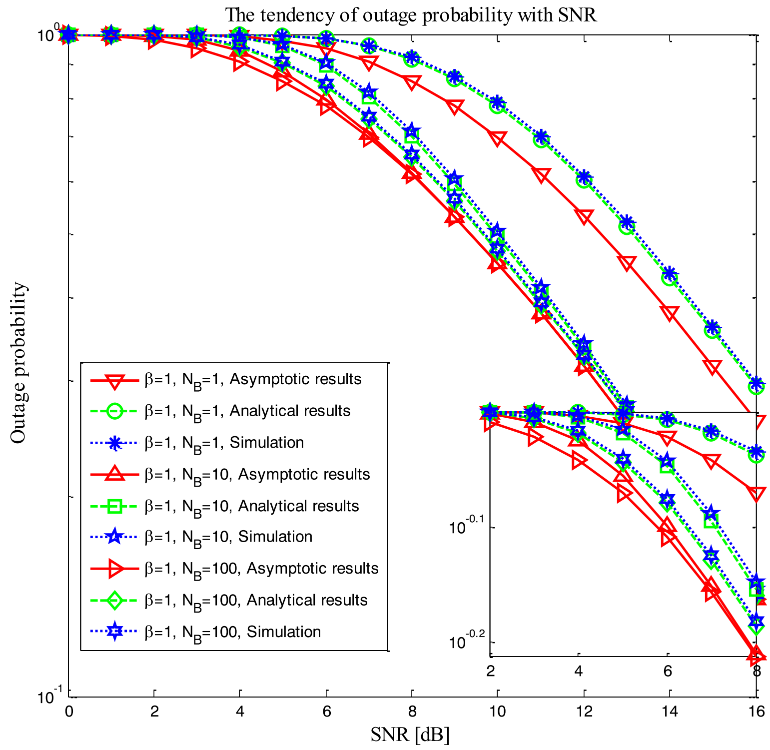

Fig. 5 The tendency of outage probability with SNR

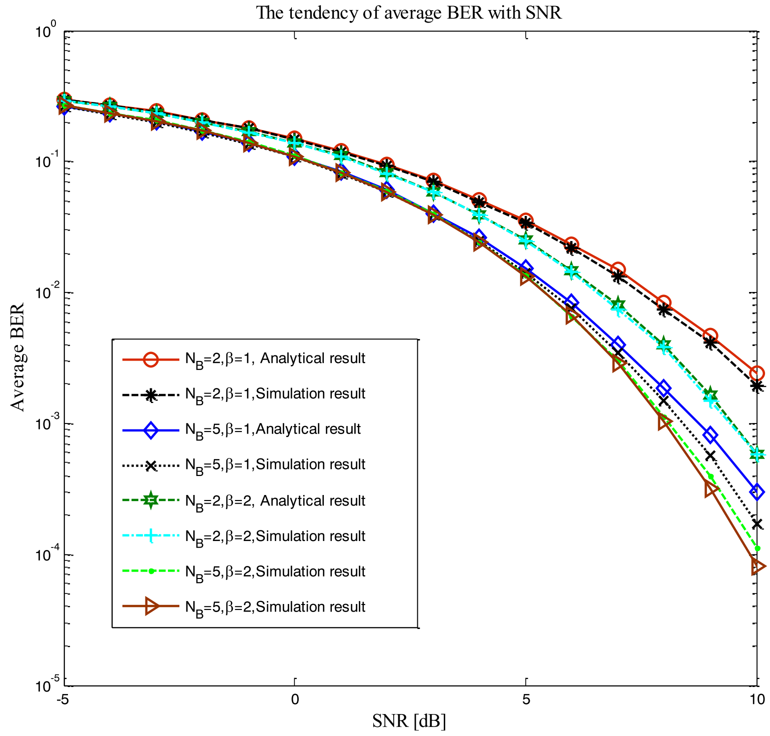

Fig. 6 The tendency of average BER with SNR

probability degrades considerably as the BS antenna or β decrease.

Figure 6 describes the correctness of the system average BER analytical results with Monte Carlo simulations. Several situations are compared in Fig. 6 to show that BS antenna number and channel parameter β have a consistent influence on the system's average BER. Similarly, system average BER decreases dramatically as $N_B$or β increase.

6 Conclusion

The full-duplex system can achieve two times the spectrum gains compared to the half-duplex. In this paper, we proposed an antenna selection scheme for FD-AF relay networks based on max-min criterion. The closed-form outage probability and BER of FD-AF relay systems in flat Gamma fading channels also were derived completely. The performance analysis results revealed that the proposed scheme is superior to the conventional scheme. We also verified our results via Monte Carlo simulations.

Appendix

This appendix mainly derives the average BER expression in the paper as follows:

Based on the approximation expression, the equivalent channel CDF after BS antenna selection can be expressed as (28):

$$P_{\gamma_e}(z) = 1-\left[1-\left(1-e^{-\frac{z}{\tilde{\Omega}_1}}\right)^{N_B}\right]\cdot\frac{\Gamma(\alpha,\beta z)}{\Gamma(\alpha)} \tag{28}$$

Then, the P_{γ_e}can be calculated through binomial theorem as:

$$P_{\gamma_e}(z) = 1-\frac{\Gamma(\alpha,\beta z)}{\Gamma(\alpha)}+\sum_{i=0}^{N_B} C_{N_B}^{i}\cdot(-1)^{i}\cdot e^{-\frac{iz}{\tilde{\Omega}_1}}\cdot\frac{\Gamma(\alpha,\beta z)}{\Gamma(\alpha)} \tag{29}$$

The general average BER mathematical expression can be defined as [30]:

$$P_e \approx \frac{1}{2}\int_0^{\infty} t_1 Q\left(\sqrt{2t_2 z}\right)p_{\gamma_e}(z)dz \tag{30}$$

where t_1 and t_2 are modulation coefficient and $Q(\cdot)$ is tail function of normal distribution and satisfies:

$$Q(x) = \frac{1}{2\pi}\int_x^{\infty}\exp\left(-\frac{u^2}{2}\right)du \tag{31}$$

Therefore, P_e can be rewritten as:

$$\begin{aligned}
P_e &\approx \frac{1}{2}\int_0^{\infty} t_1 Q\left(\sqrt{2t_2 z}\right)p_{\gamma_e}(z)dz\\
&= \frac{t_1\sqrt{t_2}}{4\sqrt{\pi}}\int_0^{\infty}\frac{e^{-t_2 z}}{\sqrt{z}}P_{\gamma_e}(z)dz\\
&= \frac{t_1\sqrt{t_2}}{4\sqrt{\pi}}\int_0^{\infty}\frac{e^{-t_2 z}}{\sqrt{z}}\left[1-\frac{\Gamma(\alpha,\beta z)}{\Gamma(\alpha)}+\sum_{i=0}^{N_B} C_{N_B}^{i}\cdot(-1)^{i}\cdot e^{-\frac{iz}{\tilde{\Omega}_1}}\cdot\frac{\Gamma(\alpha,\beta z)}{\Gamma(\alpha)}\right]dz\\
&= \frac{t_1\sqrt{t_2}}{4\sqrt{\pi}}\frac{\beta^{\alpha}\Gamma\left(\alpha+\frac{1}{2}\right)}{(\beta+t_2)^{\alpha+\frac{1}{2}}\Gamma(\alpha+1)}\,{}_2F_1\left(1,\alpha+\frac{1}{2};\alpha+1;\frac{\beta}{\beta+t_2}\right)\\
&\quad+\frac{t_1\sqrt{t_2}}{4\sqrt{\pi}}\sum_{i=0}^{N_B} C_{N_B}^{i}(-1)^{i}\frac{2\beta^{\alpha}\Gamma\left(\alpha+\frac{1}{2}\right)}{\left(\beta+t_2+\frac{i}{\tilde{\Omega}_1}\right)^{\alpha+\frac{1}{2}}\Gamma(\alpha)}\,{}_2F_1\left(1,\alpha+\frac{1}{2};\frac{3}{2};\frac{t_2+\frac{i}{\tilde{\Omega}_1}}{\beta+t_2+\frac{i}{\tilde{\Omega}_1}}\right)
\end{aligned} \tag{32}$$

Abbreviations

3GPP: Third Generation Partnership Project; AF: Amplify and forward; AS: Antenna selection; BER: Bit error ratio; BS: Base station; CDF: Cumulative distribution function; CSI: Channel state information; FD relay: Full-duplex relay; HD: Half duplex; LTE: Long-term evolution; MIMO: Multiple-input multiple-output; PDF: Probability density function; TDD: Time division duplex

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Availability of data and materials

The simulation data supporting this paper can be found and part source files can be shared.

Authors' contributions

BF J, YW, and HM are commonly derived the outage probability and BER expressions, especially the series and integrals. YQ L and GZ simulate the system performance and verify the correctness of the derivations. HW and LS modify the paper writing and smooth the words in the paper. All authors read and approved the final manuscript.

Competing interests

The authors declare that they have no competing interests.

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