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Research Article

Full-Duplex Mode in Amplify-and-Forward Relay Channels: Outage Probability and Ergodic Capacity

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This paper investigates the outage probability and ergodic capacity performances for full-duplex mode in two-way amplify-and-forward relay channels. The two-way relay channels which consist of two source nodes and a single relay node working in full-duplex mode, are assumed as independent and identically distributed as Rayleigh fading. The self-interference or loop interference of the relay is unavoidably investigated for full-duplex mode. And the close-form expressions for the outage probability and ergodic capacity of full-duplex mode are derived, considering both loop interference and the coefficients of two-way relay amplify-and-forward channels. To further facilitate the performance of full-duplex mode, the half-duplex modes over different transmission time slots are analyzed. Simulation results point out the effect of loop interference on outage probability and ergodic capacity of two-way amplify-and-forward relay channels with full-duplex mode and show that full-duplex mode can achieve better performance in terms of capacity and even outperform half-duplex modes in the presence of loop interference.

1. Introduction

Next-generation wireless communication requires higher spectral efficiency and broad coverage to support the quality of service (QoS) needed for a wide variety of multimedia applications. Two-hop communication via relay nodes is an attractive solution for hot-spot capacity enhancement, network coverage extension, and gap filling in the next-generation cellular systems, which is a promising technique to provide reliable transmission, higher throughput, and more extensive coverage [1–3]. And much research has been devoted to the relaying transmission schemes [4, 5].

The relay node assists transmission by forwarding message from source to destination, where several cooperative protocols are usually introduced, including amplify-and-forward (AF) and decode-and-forward (DF) schemes. However, traditional transmission scenarios are always with one-way relay which is mostly assumed to be half-duplex (HD) mode, resulting in an inherent spectral efficiency loss and poor utilization of resources [6]. To overcome the shortcomings and improve the performance of relay channels, two-way relay channels and full-duplex (FD) mode are taken into consideration in relay networks research. It may be better to tolerate some loop interference with full-duplex mode than to consume channel resources by allocating two orthogonal channels with half-duplex mode [7, 8].

For two-way relay channels, bidirectional communication between two sources becomes possible. Normally, half-duplex mode, as a widely used strategy of relay transmission schemes, has been discussed in much research. In two-way relay channels with half-duplex mode, the data is transmitted between sources and relay in different time slots to avoid the influence of interference caused by relay self-feedback. According to [9], two-time-slot physical-layer network coding (PNC) scheme offers a higher maximum sum rate and a lower sum bit error rate (BER) than four-time-slot transmission scheme, while three-time-slot PNC scheme offers a good compromise between two- and four-time-slot transmission schemes. Half-duplex mode in two-way relay channels can achieve a good performance for certain practical scenarios. However, due to the limitation of resource utilization, the performance of half-duplex mode seems to be not perfect and may be further improved, compared to full-duplex mode which has attracted intensive research attention recently [10].

Considering full-duplex mode in two-way AF relay channels, the relay amplifies and forwards signals to the destination, meanwhile receiving the signals from the source, which save the time and space resources of transmission and can obviously bring in an improvement of the capacity. As for simultaneous transmission and reception on the same frequency in full-duplex mode, all practical implementations suffer a significant level of loop interference (LI) or self-interference and signal leakage between transmission and reception at the relay. Though it can be reduced by employing spatially separated transmitting and receiving antennas along with interference cancellation techniques [11], loop interference is always inevitable and has a significant effect on the performance of the full-duplex relay. In the following, we will study the performance of FD mode, mainly about the outage probability and ergodic capacity in two-way AF relay channels and the effect of loop interference on the performance.

In this paper, a system model with the two-way AF relay channels is considered, in which the relay works in FD mode. In two relay channels, the source and destination nodes, each with one antenna, exchange their own data via a relay node with two antennas using an AF protocol over different time slots. The fading channels between relay and source nodes are assumed independent and identical distributed as Rayleigh, and the loop interference channels are approximated non-fading and simplified to be additive white Gaussian noise channel [12, 13]. The close-form expressions of outage probability and ergodic capacity are derived, and the effects of LI on them are analyzed. Finally, simulation results show that FD mode can tolerate high loop interference power while achieving the same capacity as HD mode. From the performance comparison of different relaying transmission modes, we can conclude that full-duplex mode can conduct pretty well and get an improvement of performance on the capacity.

The rest of the paper is organized as follows. In Section 2, we introduce the system model of two-way amplify-and-forward relay channels in FD mode. In Section 3, we derive outage probability and capacity expressions of FD mode. Then to facilitate the performance comparison of the FD and HD modes, the theoretical analyses and numerical simulation are given out in Section 4. Finally, conclusions are drawn in Section 5.

2. System Model

In this section, we introduce two-way AF relay channels in which the relay works in FD mode [14–16]. And the following FD transmission scheme is conducted actually based on this model. Consider two-way relay channels where two source nodes, A and B, communicate with each other through the aid of a relay node (R) using an AF protocol, as shown in Figure 1. For the FD relay, the loop interference should be considered because the FD relay receiving and transmitting signals are on the same frequency.

In the channel model, according to the related papers [17, 18], assuming that the relay node is fixed, we can reasonably approximate that the loop interference channel is nonfading. To relax our approach of analyzing performance with closed-form mathematical expressions, the most realistic results could be obtained by simulating a system with the Rice-fading channels. To resort to simulations, the best approximation is the additive white Gaussian noise (AWGN) channel assumed in our analysis. Source A or B is considered to be a mobile terminal without line-of-sight connection to the relay. Thus, we model the bidirectional channels between relay and A or B as quasi-static Rayleigh fading, which are independent and identically distributed. The system comprises such wireless links, namely, AR, RA, BR, RB, and residual loop interference (LI) channels represented by h_{AR}, h_{RA}, h_{BR}, h_{RB}, and h_{LI}, respectively, which also represent the channel coefficients distributed as Rayleigh and are well known at sources A and B. Furthermore, we assume that the channels AR, RA, RB, and BR are subject to block fading. In addition, normalized transmit powers of A or B and the relay are denoted by $p_A = 1$, $p_B = 1$, and $p_R = 1$.

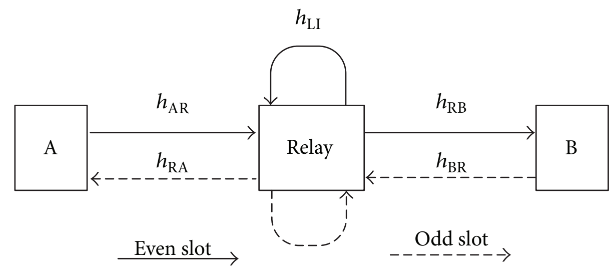

Figure 1: Two-way AF relay channels with full-duplex mode.

2.1. Transmission Scheme of FD Mode. In FD mode, sources A and B communicate with each other over three time slots as shown in Table 1. In the first time slot, source A transmits to the relay node, and simultaneously the relay node amplifies and forwards the received signals to source B. In the second time slot, B transmits to the relay node, and simultaneously the relay node amplifies and forwards the received signals to A. Thus during n time slots, $(n-2)$ symbols are exchanged between A and B.

In the odd $(2i-1, i = 2, 3\ldots)$ time slots, the data is transmitted in the direction from A to B. A transmits signal $x_A(2i-1)$ to R with a normalized transmit power $\varepsilon\{|x_A(2i-1)|^2\} = 1$, where $\varepsilon\{\cdot\}$ denotes average over signal or noise power. R receives a combination of the signal transmitted by A, loop interference, and noise:

$$r(2i-1) = h_{AR}\cdot x_A(2i-1) + h_{LI}\cdot t(2i-1) + n_R(2i-1), \quad (1)$$

where the power of the noise term n_R is $\varepsilon\{|n_R|^2\} = \sigma_R^2$.

If R exploits any loop interference cancellation algorithm, h_{LI} represents the residual channel due to imperfect cancellation. The relay amplifies the input signal by a factor $\beta > 0$ which induces a processing delay of $\tau \geq 1$ symbols. Here $\tau = 2$, as the AF relay amplifies and forwards the signal

Table 1: Transmission scheme of full-duplex mode.

Time slot	1	2	3	4	5	6	···	$2i-1$	$2i$	···
A to R	$x_A(1)$		$x_A(3)$		$x_A(5)$		···	$x_A(2i-1)$		···
B to R		$x_B(2)$		$x_B(4)$		$x_B(6)$	···		$x_B(2i)$	···
R to B			$t(3)$		$t(5)$		···	$t(2i-1)$		···
R to A				$t(4)$		$t(6)$	···		$t(2i)$	···

received two time slots before. Thus, the transmitted signal of the relay is

$$t(2i-1) = \beta \cdot r(2i-1-\tau) = \beta \cdot r(2i-3). \quad (2)$$

Then, the received signal in source B is given by

$$y_B(2i-1) = h_{RB} \cdot t(2i-1) + n_B(2i-1), \quad (3)$$

where the power of the noise term n_B is $\varepsilon\{|n_B|^2\} = \sigma_B^2$.

Similarly, in the even ($2i$, $i = 2, 3\ldots$) time slots, B transmits signal $x_B(2i)$ to R with a normalized transmit power $\varepsilon\{|x_B(2i)|^2\} = 1$. For the full-duplex relay, R receives a combination of the signal transmitted by B, loop interference, and noise:

$$r(2i) = h_{BR} \cdot x_B(2i) + h_{LI} \cdot t(2i) + n_R(2i), \quad (4)$$

where h_{BR} represents the B-relay channel, and the transmitted signal of the relay is

$$t(2i) = \beta \cdot r(2i-\tau) = \beta \cdot r(2i-2). \quad (5)$$

Finally, the received signal in source A is given by

$$y_A(2i) = h_{RA} \cdot t(2i) + n_A(2i), \quad (6)$$

where the power of the noise term n_A is $\varepsilon\{|n_A|^2\} = \sigma_A^2$.

2.2. Transmission Schemes of HD Mode. According to transmission time slots and the processing method of relay forwarding signals, the transmission schemes with HD mode include three-time-slot scheme with PNC and four-time-slot transmission scheme without PNC, as shown in Figure 2. In literature, another normalization allows double power in HD mode because the relay uses half of the channel resources. This approach is not adopted in this paper, because we impose strict limits for the instantaneous transmit power.

The four-time-slot transmission scheme without PNC can be just turned out from the above transmission scheme with FD mode, while transmission time slots extended twice and there is no loop interference. And the two- and three-time-slot schemes with PNC have been mentioned in the related papers [19, 20]. The relay node is considered as receiving the signals from A and B together and transmitting the sum of the received signals after physical network coding. The performance of these three transmission schemes with HD mode will be analyzed and set as the baselines for comparison with that of FD mode in the next section.

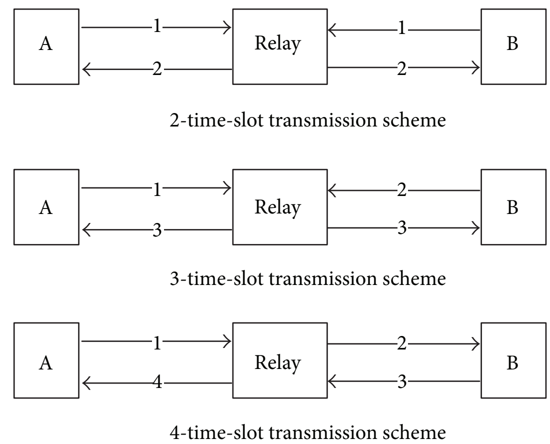

Figure 2: Two-way AF relay channels with different half-duplex modes.

3. Performance Analysis

In this section, we derive the outage probability and ergodic capacity of two-way AF relay channels with FD mode. The expressions of them are given out to analyze the relative performance. Specially, the ergodic capacity of FD mode is illustrated by plotting ergodic capacity as a function of channel SNR and is analyzed for comparing with HD mode [21, 22].

3.1. Received SINR. Firstly, we make some preliminary observations on the received instantaneous signal to interference and noise ratio (SINR) at source A or B in two-way AF relay channels with FD mode. We start with the analysis of the relay channels AR and RB. According to (1), (2), (4), and (5), the transmitted signal of R at the $(2i-1)$ time slot can be denoted as follows by recursive substitution:

$$t(2i-1) = \beta \sum_{j=1}^{\infty} (h_{LI}\beta)^{j-1} \{h_{AR}x(2i-1-2j) + n_R(2i-1-2j)\}. \quad (7)$$

The signal and noise power are $\varepsilon\{|x_A(2i-1)|^2\} = 1$ and $\varepsilon\{|n_R|^2\} = \sigma_R^2$, respectively. Furthermore, assuming that all signal and noise are mutually independent, the instantaneous relay transmit power can be expressed as

$$\varepsilon\left\{|t(2i-1)|^2\right\} = \beta^2 \sum_{j=1}^{\infty} \left(|h_{LI}|^2 \beta^2\right)^{j-1} \left(|h_{AR}|^2 + \delta_R^2\right)$$

$$= \beta^2 \frac{|h_{AR}|^2 + \delta_R^2}{1 - |h_{LI}|^2 \beta^2}, \tag{8}$$

if $\beta^2 < 1/|h_{LI}|^2$. From the expressions above, we can see that the transmitted signal of R at some time slot can be considered as the sum of the received signal and loop interference of previous infinite time slots. The channels between the relay and sources are quasi-static Rayleigh fading, and the channel coefficients can be considered dependent on time slot but dynamic equilibrium. Thus, the amplification factor β is dependent on the channel coefficients and selected to guarantee the same instantaneous transmit power. Then by assuming that the transmit power of R is $\varepsilon\{|t(2i-1)|^2\} = p_R = 1$, the amplification factor β can be solved from the expression (8) to admit the form

$$\beta = \left[|h_{AR}|^2 + \left(|h_{LI}|^2 + \delta_R^2\right)\right]^{-1/2}. \tag{9}$$

Here for source B, the received signal at time slot $2i-1$ can be further derived from the expressions (1), (2), and (3):

$$\begin{aligned} y_B(2i-1) &= h_{RB}\beta h_{AR} x_A(2i-3) \\ &\quad + h_{RB}\beta\{h_{LI}\, t(2i-3) + n_R(2i-3)\} + n_B(2i-1), \end{aligned} \tag{10}$$

which is a sum of desired signal, loop interference, and noise at source B. As mentioned above, the powers of loop interference can be calculated from the expression of $\varepsilon\{|t(2i-1)|^2\}$ in expression (7), and the power of desired signal and noise are $\varepsilon\{|x_A(2i-1)|^2\} = 1$, $\varepsilon\{|n_R|^2\} = \sigma_R^2$, and $\varepsilon\{|n_B|^2\} = \sigma_B^2$, respectively. Under the condition of signal and noise independence, the expression of instantaneous receive power at source B can be reorganized into a power sum of desired signal, loop interference, and noise power:

$$\begin{aligned} \varepsilon\left\{|y_B(2i-1)|^2\right\} &= |h_{RB}|^2\beta^2|h_{AR}|^2 \\ &\quad + |h_{RB}|^2\beta^2\left(|h_{LI}|^2\beta^2\frac{\left(|h_{AR}|^2 + \delta_R^2\right)}{1 - |h_{LI}|^2\beta^2} + \delta_R^2\right) + \delta_B^2. \end{aligned} \tag{11}$$

By dividing the desired signal power by the interference and noise power, the instantaneous SINR of B can be expressed from (9) with simplification as

$$\begin{aligned} r_B &= \left(|h_{AR}|^2|h_{RB}|^2\right) \\ &\quad \times\left(\left(\frac{\left(|h_{AR}|^2 + \delta_R^2\right)|h_{LI}|^2}{1/\beta^2 - |h_{LI}|^2} + \delta_R^2\right)|h_{RB}|^2 + \frac{\delta_B^2}{\beta^2}\right)^{-1}. \end{aligned} \tag{12}$$

Similarly for source A, the instantaneous SINR can be expressed as follows:

$$\begin{aligned} r_A &= \left(|h_{BR}|^2|h_{RA}|^2\right) \\ &\quad \times\left(\left(\frac{\left(|h_{BR}|^2 + \delta_R^2\right)|h_{LI}|^2}{1/\beta^2 - |h_{LI}|^2} + \delta_R^2\right)|h_{RA}|^2 + \frac{\delta_A^2}{\beta^2}\right)^{-1}. \end{aligned} \tag{13}$$

In the following, we parameterize the system with channel signal-to-noise ratio (SNR) values to simplify notations. The instantaneous channel SNRs are defined as $r_{AR} = |h_{AR}|^2/\delta_R^2$, $r_{RA} = |h_{RA}|^2/\delta_A^2$, $r_{BR} = |h_{BR}|^2/\delta_R^2$, $r_{RB} = |h_{RB}|^2/\delta_B^2$, and $r_{LI} = |h_{LI}|^2/\delta_R^2$. Similarly, the average channel SNRs are defined as $\bar{r}_{AR} = \varepsilon_h\{|h_{AR}|^2\}/\delta_R^2$, $\bar{r}_{RA} = \varepsilon_h\{|h_{RA}|^2\}/\delta_A^2$, $\bar{r}_{BR} = \varepsilon_h\{|h_{BR}|^2\}/\delta_R^2$, $\bar{r}_{RB} = \varepsilon_h\{|h_{RB}|^2\}/\delta_B^2$, and $\bar{r}_{LI} = \varepsilon_h\{|h_{LI}|^2\}/\delta_R^2$, where $\varepsilon_h\{\cdot\}$ denotes average over channel coefficients.

Finally, by substituting the amplification factor β from (9) and invoking the assumption on the channels SNRs, the instantaneous SINRs of A and B in two-way AF relay channels with FD mode are given by

$$\begin{aligned} r_B &= \frac{r_{AR}\cdot r_{RB}}{r_{AR} + (r_{RB}+1)(r_{LI}+1)}, \\ r_A &= \frac{r_{BR}\cdot r_{RA}}{r_{BR} + (r_{RA}+1)(r_{LI}+1)}. \end{aligned} \tag{14}$$

3.2. Outage Probability. The outage probability for the received SNR is an important quality of service measure defined as the probability that the received SNR drops below an acceptable SNR threshold r_{th}. Here we just analyze the outage probability of source B, which is related to the instantaneous SNR r_{AR}, r_{RB}, and r_{LI}, and the curve of outage probability as the function of SNR threshold r_{th} is plotted in the next section.

According to the assumption of two-way AF relay channels with FD mode, the loop interference channel is approximated non-fading; that is, $r_{LI} = \bar{r}_{LI}$. And the bidirectional channels (AR/RA and RB/BR) are independent and identically distributed as Rayleigh block fading; $\bar{r}_{AR} = \bar{r}_{RA}$ and $\bar{r}_{BR} = \bar{r}_{RB}$, respectively. The instantaneous channel SNR r becomes an exponential random variable with average SNR $\bar{r}$ and probability distribution function $f_{\bar{r}}(r) = (1/\bar{r})\exp(-r/\bar{r})$. Here, for the transmission from source A to B, the instantaneous SNR r_{AR} and r_{RB} submit

$$\begin{aligned} f_{\bar{r}_{AR}}(r_{AR}) &= \frac{1}{\bar{r}_{AR}}\exp\left(-\frac{r_{AR}}{\bar{r}_{AR}}\right), \\ f_{\bar{r}_{RB}}(r_{RB}) &= \frac{1}{\bar{r}_{RB}}\exp\left(-\frac{r_{RB}}{\bar{r}_{RB}}\right). \end{aligned} \tag{15}$$

Then we can denote the outage probability of the received SNR at source B as

$$\begin{aligned}
&P\left(r_B < r_{\text{th}}\right) \\
&= P\left(\frac{r_{\text{RB}} \cdot r_{\text{AR}}}{r_{\text{RB}} + \left(r_{\text{AR}} + 1\right)\left(\overline{r}_{\text{LI}} + 1\right)} < r_{\text{th}}\right) \\
&= \iint_{r_B < r_{\text{th}}} f_{\overline{r}_{\text{AR}}}(x)\, f_{\overline{r}_{\text{RB}}}(y)\, dx\, dy \\
&= \int_0^{(\overline{r}_{\text{LI}}+1)r_{\text{th}}} f_{\overline{r}_{\text{RB}}}(y) \int_0^{\infty} f_{\overline{r}_{\text{AR}}}(x)\, dx\, dy \\
&\quad + \int_{(\overline{r}_{\text{LI}}+1)r_{\text{th}}}^{\infty} f_{\overline{r}_{\text{RB}}}(y) \int_0^{(y+\overline{r}_{\text{LI}}+1)r_{\text{th}}/(y-(\overline{r}_{\text{LI}}+1)r_{\text{th}})} f_{\overline{r}_{\text{AR}}}(x)\, dx\, dy \\
&= 1 - \int_{(\overline{r}_{\text{LI}}+1)r_{\text{th}}}^{\infty} \frac{1}{\overline{r}_{\text{AR}}} \\
&\qquad \times e^{-((1/\overline{r}_{\text{AR}})y + (1/\overline{r}_{\text{RB}})((y+\overline{r}_{\text{LI}}+1)r_{\text{th}}/(y-(\overline{r}_{\text{LI}}+1)r_{\text{th}})))} dy.
\end{aligned} \tag{16}$$

Besides the SNR threshold, the outage probability of received SNR at source B is also affected by the average SNR $\overline{r}_{\text{AR}}$, $\overline{r}_{\text{RB}}$, and $\overline{r}_{\text{LI}}$ which depends on loop interference power. Specially, assuming the fading channels AR and RB are identically distributed, that is, $\overline{r}_{\text{RB}} = \overline{r}_{\text{AR}}$, sources A and B in two-way AF relay channels can be considered equivalent, whose performance of outage probability can be similarly devoted. Then the expression (16) will be further derived as

$$\begin{aligned}
&P\left(r_{\text{B}} < r_{\text{th}}\right) \\
&\quad = 1 - \int_{(\overline{r}_{\text{LI}}+1)r_{\text{th}}}^{\infty} \frac{1}{\overline{r}_{\text{AR}}} \\
&\qquad \times e^{-(1/\overline{r}_{\text{AR}})(y + ((y+\overline{r}_{\text{LI}}+1)r_{\text{th}}/(y-(\overline{r}_{\text{LI}}+1)r_{\text{th}})))} dy \\
&\quad = -1 - \int_0^{\infty} \frac{1}{\overline{r}_{\text{AR}}} \\
&\qquad \times e^{-(1/\overline{r}_{\text{AR}})(y + ((\overline{r}_{\text{LI}}+1)(r_{\text{th}}+1)/y) + (\overline{r}_{\text{LI}}+1)(r_{\text{th}}+1))} dy \\
&\quad = 1 - \frac{2\left(\overline{r}_{\text{LI}}+1\right)^{1/2}\left(r_{\text{th}}+1\right)^{1/2}}{\overline{r}_{\text{AR}}} e^{-(\overline{r}_{\text{LI}}+1)(r_{\text{th}}+1)/\overline{r}_{\text{AR}}} \\
&\qquad \times K_{-1}\left(\frac{2\left(\overline{r}_{\text{LI}}+1\right)^{1/2}\left(r_{\text{th}}+1\right)^{1/2}}{\overline{r}_{\text{AR}}}\right),
\end{aligned} \tag{17}$$

which is simplified in terms of the modified Bessel functions $K_v(xz) = (z^v/2)\int_0^{\infty} \exp(-(x/2)(t + (z^2/t)))t^{(-v-1)} dt$.

3.3. Ergodic Capacities. For the two-way AF relay channels, the ergodic capacity can mainly reflect the performance of relaying transmission mode. According to the instantaneous SINR derived in (14) and the channel fading distribution in (15), the ergodic capacity of two-way AF relay channels with FD mode is derived as

$$\begin{aligned}
C_{\text{FD}} &= \varepsilon\left\{\log_2(1+r)\right\} \\
&= \iint_0^{\infty} \log_2(1+r)\, f_{\overline{r}_{\text{RB}}}(x)\, f_{\overline{r}_{\text{AR}}}(y)\, dx\, dy \\
&= \iint_0^{\infty} \log_2\left(1 + \frac{xy}{y + (x+1)\left(\overline{r}_{\text{LI}}+1\right)}\right) \\
&\qquad \times f_{\overline{r}_{\text{RB}}}(x)\, f_{\overline{r}_{\text{AR}}}(y)\, dx\, dy \\
&= \int_0^{\infty} \lambda_1 e^{-\lambda_1 x} \int_0^{\infty} \log_2(e)\, e^{-\lambda_2 y} \\
&\qquad \times \left(\frac{1}{y + \left(r_{\text{LI}}+1\right)} - \frac{1}{y + (x+1)\left(r_{\text{LI}}+1\right)}\right) dy\, dx,
\end{aligned} \tag{18}$$

where $\lambda_1 = 1/\overline{r}_{\text{RB}}$, $\lambda_2 = 1/\overline{r}_{\text{AR}}$, and $r_{\text{LI}} = \overline{r}_{\text{LI}}$. And the last expression is obtained by integrating in parts, and it is simplified as follows in terms of the exponential integral $\text{Ei}(z) = \int_1^{\infty}(e^{-zt}/t)dt = \int_z^{\infty}(e^{-t}/t)dt$:

$$\begin{aligned}
C_{\text{FD}} &= \frac{\lambda_1}{\log_e 2}\left(\int_0^{\infty} e^{\lambda_2(r_{\text{LI}}+1)-\lambda_1 x}\text{Ei}\left(\lambda_2\left(r_{\text{LI}}+1\right)\right) dx \right. \\
&\qquad - \int_0^{\infty} e^{\lambda_2(x+1)(r_{\text{LI}}+1)-\lambda_1 x} \\
&\qquad \left. \times \text{Ei}\left(\lambda_2(x+1)\left(r_{\text{LI}}+1\right)\right) dx\right) \\
&= \frac{e^{\lambda_2(r_{\text{LI}}+1)}\text{Ei}\left(\lambda_2\left(r_{\text{LI}}+1\right)\right)}{\log_e 2} \\
&\quad - \frac{\lambda_1 \int_0^{\infty} e^{\lambda_2(x+1)(r_{\text{LI}}+1)-\lambda_1 x}\text{Ei}\left(\lambda_2(x+1)\left(r_{\text{LI}}+1\right)\right) dx}{\log_e 2} \\
&= \frac{e^{\lambda_2(r_{\text{LI}}+1)}\text{Ei}\left(\lambda_2\left(r_{\text{LI}}+1\right)\right)}{\log_e 2} \\
&\quad + \frac{\lambda_1 e^{\lambda_2(r_{\text{LI}}+1)}\text{Ei}\left(\lambda_2\left(r_{\text{LI}}+1\right)\right) - \lambda_1 e^{\lambda_1}\text{Ei}\left(\lambda_1\right)}{\left(\left(r_{\text{LI}}+1\right)\lambda_2 - \lambda_1\right)\log_e 2} \\
&= \frac{\left(r_{\text{LI}}+1\right)\lambda_2 e^{\lambda_2(r_{\text{LI}}+1)}\text{Ei}\left(\lambda_2\left(r_{\text{LI}}+1\right)\right) - \lambda_1 e^{\lambda_1}\text{Ei}\left(\lambda_1\right)}{\left(\left(r_{\text{LI}}+1\right)\lambda_2 - \lambda_1\right)\log_e 2}.
\end{aligned} \tag{19}$$

Similarly, assuming that the fading channels AR and RB are identically distributed, the expression of ergodic capacity (19) can be simplified for $\lambda_1 = \lambda_2$:

$$C_{\text{FD}} = \frac{\lambda_1\left(r_{\text{LI}}+1\right)e^{\lambda_1(r_{\text{LI}}+1)}\text{Ei}\left(\lambda_1\left(r_{\text{LI}}+1\right)\right) - \lambda_1 e^{\lambda_1}\text{Ei}\left(\lambda_1\right)}{r_{\text{LI}}\log_e 2}. \tag{20}$$

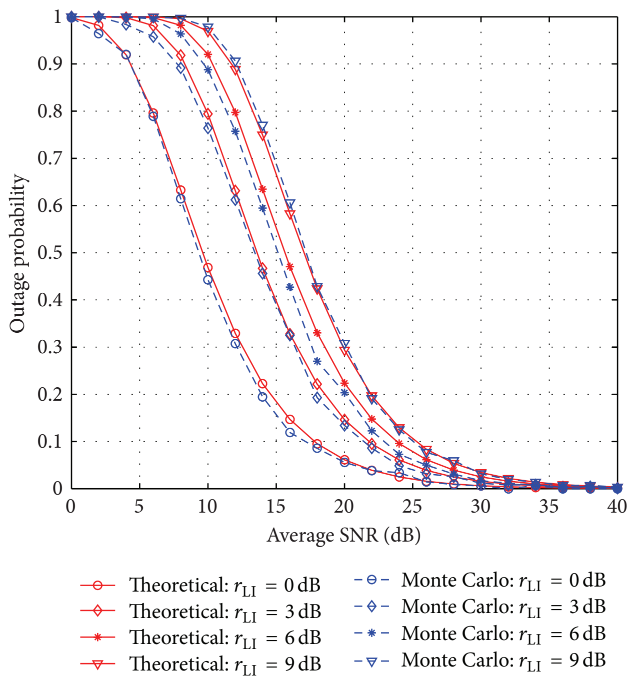

Figure 3: Comparison of outage probability with FD mode between theoretical and Monte Carlo simulation results, when r_{th} = 5 dB and average SNR $\overline{r}_{AR} = \overline{r}_{RB}$.

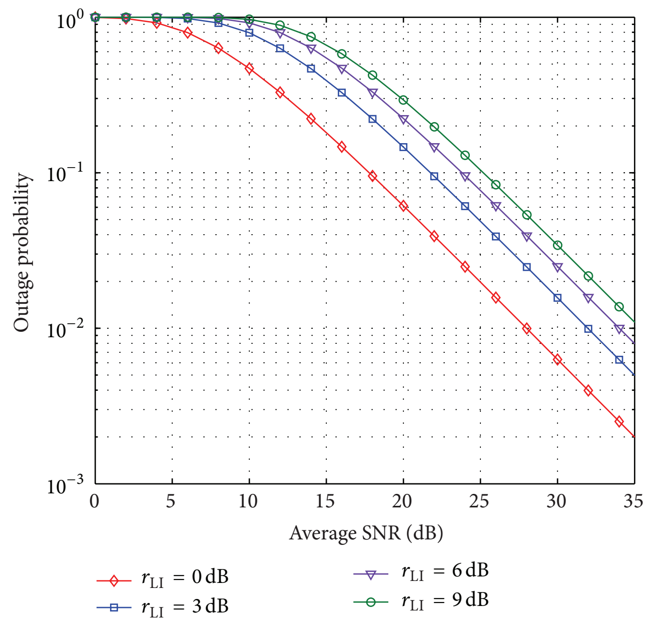

Figure 4: Outage probability of FD mode with different loop interference, when r_{th} = 5 dB and average SNR $\overline{r}_{AR} = \overline{r}_{RB}$.

By using the analytical expression, the relative performance simulation of the FD mode will be further investigated, offering a comparison with HD mode of different transmission schemes which are used practically. And in the next section, we will show that FD mode may have a perfect performance and outperforms HD mode in some scenarios.

4. Simulation Results

For the two-way AF relay channels, as sources A and B are independent and symmetrical, we just give out the performance simulations of source B, which is equivalent to A. In the following, we first analyze and simulate the outage probability of two-way AF relay channels with FD mode. To simplify the theoretical simulation, the outage probability is analyzed according to the expressions (16) and (17) in which $\overline{r}_{AR} = \overline{r}_{RB}$ and the fading channels AR and RB are assumed to be identically distributed.

As shown in Figure 3, the simulation results of outage probability in FD mode are given out for the comparison between theoretical and Monte Carlo simulation, when r_{th} = 5 dB and average SNR $\overline{r}_{AR} = \overline{r}_{RB}$. The results of Monte Carlo simulation are quite suitable with the theoretical analytical ones in the presence of different LI, which actually justify the derivation of outage probability of FD mode above.

In Figure 4, the outage probability of received SNR at source B of the function to the average SNR ($\overline{r}_{AR}$) is investigated at the scenario where SNR threshold is set at 5 dB. The simulation result illustrates that the outage probability decreases as average SNR $\overline{r}_{AR}$ (or $\overline{r}_{RB}$) increases. Especially, the outage probability is approaching zero in the high SNR region when $(\overline{r}_{AR}) > 30$. On the other hand, the loop interference of the relay node has a significant effect on the outage probability. With r_{LI} decreasing, the outage probability of source B which received SNR becomes lower, which leads to a worse communication quality. In FD mode, the outage probability can be improved by decreasing the loop interference of full-duplex relay. In other words, the loop interference cancellation can make the transmission quality of FD mode better.

Similarly, we first give out the ergodic capacity of source B in two-way AF relay channels with FD mode under the assumption $\overline{r}_{AR} = \overline{r}_{RB}$, according to the expressions (19) and (20). Obviously, as we can see from Figure 5, the ergodic capacity of source B increases with average SNR ($\overline{r}_{AR}$ or $\overline{r}_{RB}$) both in FD mode and HD mode. The better channel condition can bring the higher ergodic capacity.

Figure 5 also investigates the comparison of the ergodic capacity of two-way AF relay channels between FD mode and the three transmission schemes with HD mode. The ergodic capacity of FD mode can be actually superior to the other three HD modes over different transmission time slots, if the loop interference can be suppressed far below the noise level (about $\overline{r}_{LI} < 2$ dB). Specifically, when average SNR $\overline{r}_{AR}$ (or $\overline{r}_{RB}$) is over 30 dB and LI is high enough (like $\overline{r}_{LI} < 20$ dB), the ergodic capacity of FD mode still outperforms those of HD modes. On the other hand, the increasing loop interference LI also leads to the worse capacity performance, which is actually reflecting that the performance of FD mode is largely limited to the loop interference of full-duplex relay.

We can see that full-duplex relaying brings an impressive improvement of performance besides the loop interference as

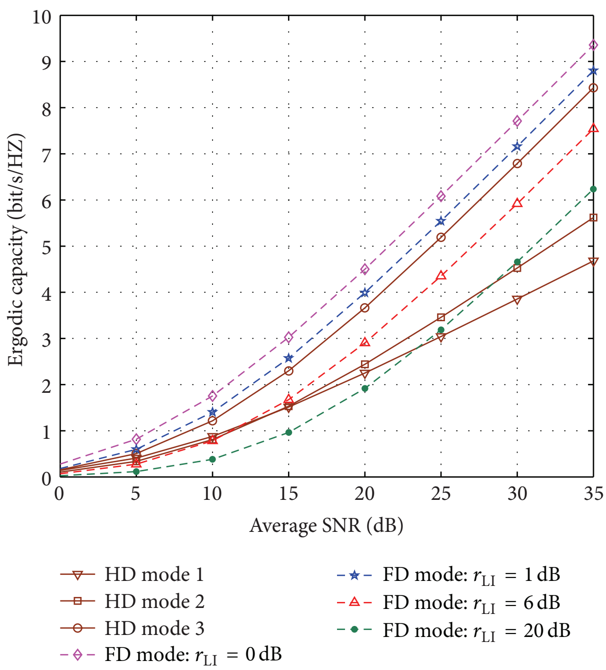

Figure 5: Ergodic capacity of FD mode with different loop interference, comparing with HD mode when average SNR $\bar{r}_{AR} = \bar{r}_{RB}$. For the baselines of HD modes, HD mode 1 represents 4-time-slot scheme, HD mode 2 represents 3-time-slot scheme, and HD mode 3 represents 2-time-slot scheme.

well. In two-way AF relay channels, FD mode can enhance the capacity along with improving efficiency of resource usage in two-hop full-duplex relay channels based on resource sharing and interference cancellation and has a better performance than HD mode in some scenarios.

5. Conclusion

In this paper, we conducted a study of two-way AF relay channels with FD mode. Assuming that the loop interference of the full-duplex relay can not be completely suppressed and the channel fading is modeled by the Rayleigh distribution, the outage probability and ergodic capacity for FD mode in two-way AF relay channels were analyzed and the close-form expressions were derived. The simulation results showed that self-interference of FD relay and the channel condition have a significant effect on outage probability and ergodic capacity. We also draw a conclusion that FD mode in two-way AF relay channels can outperform HD mode, even with a tolerable level of self-interference. It may be better to tolerate some loop interference with full-duplex mode than to consume channel resources by allocating two orthogonal channels with half-duplex mode. Based on the work, we are able to generalize the results to multiuser and multirelay networks as well as to get more useful insights [23, 24] about improving the QoS of the network by using a variety of interference management schemes like power control, multiple antennas, and so on.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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