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Adaptive AF/DF Selection With FD/HD Switching in Two-Way Relay Networks

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ABSTRACT The full-duplex (FD) and two-way relay are promising techniques for their high spectrum efficiency. However, the incompletely self-interference cancellation may reduce the performance gain of two-way relay networks, which operates in FD mode. In this paper, we propose an adaptive amplify-and-forward (AF) and decode-and-forward (DF) selection scheme for FD two-way relay networks, where the relay is allowed to operate in half-duplex (HD) mode. We first derive closed-form formulas of the outage probabilities of the non-adaptive AF and DF schemes for two-way relay networks in both FD and HD modes. To improve the outage performance, an adaptive AF/DF scheme will be proposed for two-way relay networks. However, with the residual self-inference, adaptive FD scheme is not always the best choice for achieving the optimal outage performance. Therefore, we also design an optimal switch scheme between FD and HD modes. The closed form formulas of the outage probability are also derived. The simulation results will not only verify the theoretical derivations, but also illustrate the significant performance gains compared with existing non-adaptive schemes.

INDEX TERMS Full-duplex, half-duplex, two-way relay, outage probability, amplify and forward, decode and forward.

I. INTRODUCTION

Spectrum efficiency is one of the key performance metrics for wireless communication systems. In order to achieve higher spectrum efficiency, two-way relay and full-duplex (FD) techniques are proposed. The two-way channel was first studied by Shannon [1], who derived the inner and outer bounds on their capacity region. To achieve the messages exchanging between two terminal nodes via a relay node, two-way relay half-duplex (HD) with three time slots and four time slots attracts wide research interests [2], [3]. To further improve the spectrum efficiency, a bidirectional two time slots two-way relay scheme [4]–[8] was introduced where step 3 and 4 are combined as a broadcast. Because of high spectrum efficiency, two-way relay HD scheme has been adopted in 4G mobile communication systems [9], [10]. On the other hand, the FD technique, which has been regarded as impractical before for its strong residual self-interference (RSI), comes into reality because of the development of the self interference (SI) cancellation techniques [11]–[14]. Recently, due to the performance of nearly doubled spectrum efficiency, FD technique has the potential to offer a higher spectrum efficiency to 5G mobile communication systems compared to conventional HD communications [15]. Combining the advantages of the FD and two time slots two-way relaying, the FD two-way relay networks can further improve the spectrum efficiency by achieving bidirectional messages transmission and reception on the same frequency band simultaneously.

The amplify-and-forward (AF) and the decode-and-forward (DF) are the two common protocols in the two-way relay networks. Many performance metrics such as achievable rate, ergodic capacity, and outage probability are studied in HD mode. In [8], the achievable rate of the two-way relay is investigated. In [4], Rankov and Witineben analyzed the ergodic capacity of AF and DF schemes in two-way relay HD networks. Liang *et al.* [16], [17], respectively analyzed the outage probabilities of AF and DF in two-way relay HD networks in the presence of multiple interferers at the terminal nodes. In order to increase the communication throughput of two-way relay networks in DF scheme, network coding technology was introduced. In [7], [18], and [19], network coding technology was investigated for two-way relay to exploit the broadcast nature of the wireless communication systems. Li *et al.* [20], analyzed the outage probabilities of AF and DF in two-way relay HD networks, where an adaptive switching scheme between AF and DF protocols are proposed. The proposed adaptive scheme outperforms the non-adaptive schemes.

With the development of the SI cancellation techniques in FD communications, the SI can be greatly suppressed by several ways. In [21]–[23], various antenna-based solutions were proposed. In [24]–[26], active analog domain cancellation methods were proposed. In [14], [27], and [28], digital baseband domain cancellation techniques were investigated. Moreover, in [29], the overall performances of different linear SI cancellation methods have been analyzed. Korpi *et al.* [11], addressed the problem of self-interference cancellation in FD direct-conversion radio transceivers, where a novel linear digital SI cancellation method was proposed. In [30], Masmoudi and Le-Ngoc presented a two-stage SI cancelation for FD multi-input-multi-output (MIMO) communications systems, in which the SI channel coefficients can be perfectly estimated with no knowledge of the intended signal and showed a remarkable SI cancellation effect. Nevertheless, the RSI still needs to be considered in FD communications.

The performance of FD scheme in two-way relay networks are also investigated. Hu *et al.* [31], investigated the outage probability and ergodic capacity of the AF scheme in two time slots FD two-way relay networks. Li *et al.* [32], studied the outage performance of DF scheme for two-way relay in FD scheme, which showed that the FD scheme is not always the good choice with imperfect RSI cancellation. Zhang *et al.* [33], studied the average rate and outage probability tradeoffs of AF and DF for two-way and one-way relay in FD scheme. In [34], Choi and Lee investigated the outage probability of the AF scheme in two-way relay FD networks with perfect and imperfect channel state information (CSI). Riihonen *et al.* [35], proposed a hybrid technique which switches opportunistically between FD and HD two-way relay schemes to maximize the spectrum efficiency. However, there is no adaptive AF/DF selection with FD/HD switching scheme in two-way relay networks for minimizing the outage probability.

In this paper, we first derive the closed form expressions of the outage probabilities for the non-adaptive AF and DF in two-way relay FD networks in the presence of the RSI. We then consider an adaptive AF and DF selection scheme in two-way relay FD networks. However, the RSI can not be completely eliminated by self-inference cancellation techniques, which limits the performance gain of the FD scheme. Therefore the adaptive FD scheme is not always the best choice for minimizing the outage probability. In high signal-to-noise ratio (SNR) regime, the corresponding RSI may be too large to achieve a small outage probability, which will lead to an outage. In this context, the outage performance of the adaptive HD scheme is getting better with the increase of the SNR [20]. Hence we consider an adaptive selection scheme between AF and DF in two-way relay networks with FD and HD scheme. When the SNR is smaller than a threshold $\frac{2Rth}{\xi}$, we choose the adaptive FD scheme. Otherwise, we choose the adaptive HD scheme. If it still in outage, we try the DF scheme in FD mode. The simulation results will not only verify the theoretical derivations, but also illustrate the significant performance gains when comparing to existing non-adaptive schemes.

The rest of the paper is organized as follows. Section II presents the system models of two-way relay in both FD and HD schemes. Non-adaptive outage probabilities of AF and DF schemes for two-way relay in both FD and HD modes are derived respectively in Section III. Section IV deals with the outage probabilities of the proposed adaptive AF/DF selection with FD/HD switching for two-way relay channels. Simulation results are presented in Section V. Finally, the main conclusions are drawn in Section VI.

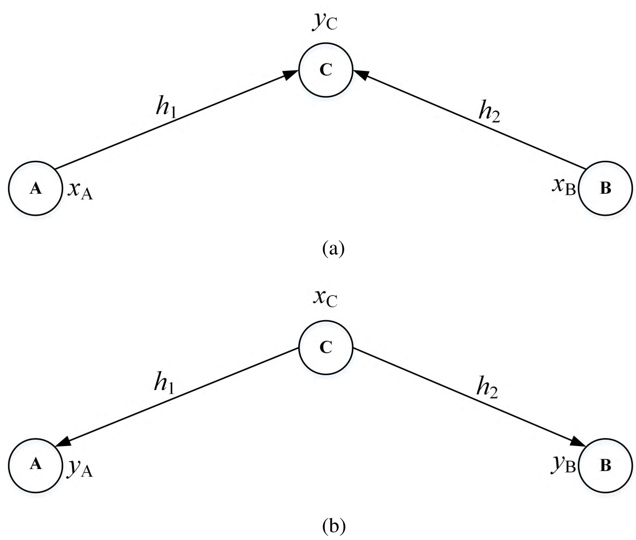

FIGURE 1. The system model of two-way relay networks. (a) Multiple access (MAC) stage. (b) Broadcast (BC) stage.

II. SYSTEM MODEL

As shown in Fig.1, node A and B exchange messages with the help of node C. All nodes switch between FD and HD schemes, and C switches between AF and DF protocols. Due to the path loss and shadowing effect, the direct link between A and B can be neglected. The transmit power at A, B, and C is assumed to be equal and denoted by P. The independent channel fading coefficients between A and C, B and C are denoted by h_1 and h_2, respectively. The channels with $h_1 \sim \mathcal{CN}(0, \lambda_1)$, $h_2 \sim \mathcal{CN}(0, \lambda_2)$ are reciprocal and subject to block fading. Then $x = |h_1|^2$ and $y = |h_2|^2$ follow the exponential distribution with the parameters

$1/\lambda_1$ and $1/\lambda_2$, whose joint probability density function is given by $f_{X,Y}(x,y) = \lambda_1\lambda_2 e^{-\lambda_1 x-\lambda_2 y}$. Also, we assume the CSI can be estimated perfectly. The variances of zero-mean additive white Gaussian noise (AWGN) n_A, n_B, and n_C at the nodes A, B, and C are assumed to be equal and denoted by σ^2. It should be noted that there are two kinds of self-interference in this model: one from FD transmission and one from two-way relay networks. Moreover, the self-interference from two-way relay networks is ignored in both FD and HD systems. A two-way relay network consists of the multiple access (MAC) and broadcast (BC) stage [4]. In the MAC stage, A and B transmit signals x_A and x_B to C simultaneously. After a certain signal processing operations, C broadcasts the received signals x_C to A and B in the BC stage. The received signals of A, B, and C are denoted by y_A, y_B, and y_C.

A. TWO-WAY RELAY IN FD MODE

In FD mode, all nodes transmit and receive signals in the same frequency band simultaneously. In each time slot, node C receives the signals from nodes A and B along with the RSI generated from its own. While A and B receive the forwarded signals, which are amplified or decoded by C, along with its own RSI. As A and B know the signals they transmit and have perfect CSI, they can subtract the self-inference to obtain the target signals. Considering the imperfect self inference cancellation (SIC), the accurate relation between the RSI and transmit power is still unknown [36]. But according to previous works [13], [32], we model the RSI as a random Gaussian variable with zero mean and variance proportional to the local transmit power, i.e. $z_A, z_B, z_C \sim \mathcal{CN}(0, \xi P)$. In the k-th time slot, the signals received by A, B, and C can be expressed as

$$y_C[k] = h_1 x_A[k] + h_2 x_B[k] + n_C[k] + z_C[k] \tag{1}$$

$$y_B[k] = h_2 x_C[k] + n_B[k] + z_B[k] \tag{2}$$

$$y_A[k] = h_1 x_C[k] + n_A[k] + z_A[k]. \tag{3}$$

In the AF scheme, after receiving the signals in the MAC stage, node C amplifies the received signals with its transmit power. Hence the transmit signals x_C can be written as

$$\begin{aligned} x_C[k] &= \rho[k] y_C[k] \\ &= \rho_1[k]\left(h_1 x_A[k] + h_2 x_B[k] + n_C[k] + z_C[k]\right), \end{aligned} \tag{4}$$

where ρ_1 is an amplification coefficient and can be written as

$$\rho_1[k] = \sqrt{\frac{P}{P|h_1[k]|^2 + P|h_2[k]|^2 + \sigma^2 + \xi P}}. \tag{5}$$

In the BC stage, by substituting (4) into (2), the received signal of node B can be written as

$$\begin{aligned} y_B[k] = h_2\rho_1[k](h_1 x_A[k] + h_2 x_B[k] + n_C[k] + z_C[k]) \\ + n_B[k] + z_B[k]. \end{aligned} \tag{6}$$

Since node B knows its own transmitted signals and has a perfect CSI estimation, it can subtract the self-interference in (6) before decoding the received signal. The remained signal at node B can be written as

$$\begin{aligned} y_B[k] = h_2\rho_1[k]h_1 x_A[k] + h_2\rho_1[k](n_C[k] + z_C[k]) \\ + n_B[k] + z_B[k]. \end{aligned} \tag{7}$$

In the DF scheme, after receiving the signals from nodes A and B, node C attempts to decode both x_A and x_B. If successfully decoding the signals, node C implements network coding [18] technique with bit-level XOR operation to recode the data stream. The forwarded signal x_C is the bitwise XOR of the x_A and x_B data streams, i.e. $x_C[k] = x_A[k] \bigoplus x_B[k]$. After receiving and decoding the broadcasted signals, nodes A and B perform bit-level XOR to obtain the desired data streams. Therefore, the remained signal at node B can be written as

$$y_B[k] = h_2 x_A[k] + n_B[k] + z_B[k]. \tag{8}$$

B. TWO-WAY RELAY IN HD MODE

In HD mode, the procedure of signal transmission is similar to that in FD mode. But the MAC and BC stages are finished in two time slots. Moreover, there is no RSI in the HD scheme. In the k-th time slot, node C receives the signals from nodes A and B, simultaneously. In the $(k+1)$-th time slot, A and B receive the forwarded signals from node C. Then they subtract the self-inference to obtain the target signals. The signals received by A, B, and C can be expressed as

$$y_C[k] = h_1 x_A[k] + h_2 x_B[k] + n_C[k] \tag{9}$$

$$y_B[k+1] = h_2 x_C[k+1] + n_B[k+1] \tag{10}$$

$$y_A[k+1] = h_1 x_C[k+1] + n_A[k+1]. \tag{11}$$

Similarly, the remained signal at node B in the AF scheme can be written as

$$y_B[k+1] = h_2\rho_2[k]h_1 x_A[k] + h_2\rho_2[k]n_C[k] + n_B[k+1], \tag{12}$$

where ρ_2 is an amplification coefficient and can be written as

$$\rho_2[k] = \sqrt{\frac{P}{P|h_1[k]|^2 + P|h_2[k]|^2 + \sigma^2}}. \tag{13}$$

The remained signal at node B in the DF scheme can be written as

$$y_B[k+1] = h_2 x_A[k] + n_B[k+1]. \tag{14}$$

III. NON-ADAPTIVE OUTAGE PROBABILITY ANALYSIS

In this section, we investigate the non-adaptive outage performances of the AF and DF schemes for two-way relay in both FD and HD mode. The target transmission rate is denoted by R_{th}. For simplicity, we only consider the high rate case where $R_{th} \geq 1$. We let $l_1 = 2^{R_{th}} - 1$, $l_2 = 2^{2R_{th}} - 1$, $t_1 = \sigma^2 + \xi P$, $t_2 = \sigma^2$ for convenience.

A. OUTAGE PROBABILITY OF NON-ADAPTIVE FD SCHEME

Proposition 1: The non-adaptive outage probabilities of the AF scheme for two-way relay in FD mode (FDAF) are respectively given by

$$p_{out-A}^{FDAF} = 1 - 2\lambda_1 e^{-\frac{t_1 l_1(2\lambda_1+\lambda_2)}{P}} \sqrt{\frac{\lambda_2 t_1^2 l_1(2l_1+1)}{\lambda_1 P^2}} \times K_{-1}\left(\sqrt{\frac{4\lambda_1\lambda_2 t_1^2 l_1(2l_1+1)}{P^2}}\right) \quad (15)$$

$$p_{out-B}^{FDAF} = 1 - 2\lambda_1 e^{-\frac{t_1 l_1(2\lambda_2+\lambda_1)}{P}} \sqrt{\frac{\lambda_1 t_1^2 l_1(2l_1+1)}{\lambda_2 P^2}}$$
$$[5pt] \qquad \times K_{-1}\left(\sqrt{\frac{4\lambda_1\lambda_2 t_1^2 l_1(2l_1+1)}{P^2}}\right), \quad (16)$$

where $K_{-1}(\cdot)$ is the modified Bessel function of the second kind [31] given by

$$K_v(xz) = (z^v/2)\int_0^\infty exp(-(x/2)(t+(z^2/t)))t^{-v-1}dt. \quad (17)$$

Proof: See Appendix A.

Proposition 2: The non-adaptive outage probabilities of the DF scheme for two-way relay in FD mode (FDDF) are respectively given by

$$p_{out-A}^{FDDF} = 1 - \frac{\lambda_1}{\lambda_1+\lambda_2 l_1} e^{-\frac{t_1 l_1(\lambda_1+\lambda_2+\lambda_2 l_1)}{P}} - \frac{\lambda_2}{\lambda_2+\lambda_1 l_1} e^{-\frac{t_1 l_1(\lambda_1+\lambda_2+\lambda_1 l_1)}{P}} \quad (18)$$

$$p_{out-B}^{FDDF} = 1 - \frac{\lambda_1}{\lambda_1+\lambda_2 l_1} e^{-\frac{t_1 l_1(\lambda_1+\lambda_2+\lambda_2 l_1)}{P}} - \frac{\lambda_2}{\lambda_2+\lambda_1 l_1} e^{-\frac{t_1 l_1(\lambda_1+\lambda_2+\lambda_1 l_1)}{P}}. \quad (19)$$

Proof: See Appendix B.

B. OUTAGE PROBABILITY OF NON-ADAPTIVE HD SCHEME

There are two main differences between FD and HD scheme. The first one is that the HD scheme uses two time slots to finish message exchanging while the FD scheme only uses one time slot. Therefore the pre-log factor of the transmission rates are $\frac{1}{2}$ due to the spectral loss in the HD scheme. The other difference is that there is no RSI in the HD scheme. Therefore we can easily get the corresponding outage probability of the AF and DF schemes for two-way relay in HD mode.

Proposition 3: The non-adaptive outage probabilities of the AF scheme for two-way relay in HD mode (HDAF) are respectively given by

$$p_{out-A}^{HDAF} = 1 - 2\lambda_1 e^{-\frac{t_2 l_2(2\lambda_1+\lambda_2)}{P}} \sqrt{\frac{\lambda_2 t_2^2 l_2(2l_2+1)}{\lambda_1 P^2}} \times K_{-1}\left(\sqrt{\frac{4\lambda_1\lambda_2 t_2^2 l_2(2l_2+1)}{P^2}}\right). \quad (20)$$

$$p_{out-B}^{HDAF} = 1 - 2\lambda_1 e^{-\frac{t_2 l_2(2\lambda_2+\lambda_1)}{P}} \sqrt{\frac{\lambda_1 t_2^2 l_2(2l_2+1)}{\lambda_2 P^2}} \times K_{-1}\left(\sqrt{\frac{4\lambda_1\lambda_2 t_2^2 l_2(2l_2+1)}{P^2}}\right). \quad (21)$$

Proposition 4: The non-adaptive outage probabilities of the DF scheme for two-way relay in HD mode (HDDF) are respectively given by

$$p_{out-A}^{HDDF} = 1 - \frac{\lambda_1}{\lambda_1+\lambda_2 l_2} e^{-\frac{t_2 l_2(\lambda_1+\lambda_2+\lambda_2 l_2)}{P}} - \frac{\lambda_2}{\lambda_2+\lambda_1 l_2} e^{-\frac{t_2 l_2(\lambda_1+\lambda_2+\lambda_1 l_2)}{P}}. \quad (22)$$

IV. OUTAGE PERFORMANCE ANALYSIS FOR ADAPTIVE AF/DF SELECTION WITH FD/HD SWITCHING

As all the nodes can select AF and DF and switch between FD and HD, we are wondering whether there is an adaptive forwarding scheme to improve the outage performance. An adaptive AF/DF selection in HD mode was proposed, which illustrates an better performance under all channel conditions and all transmit SNR values [20]. However, in FD mode the results show that the outage probability of the DF scheme for two-way relay FD scheme monotonically increase and converge to 1 as the transmit power exceeds a certain threshold [32]. Besides, it shows that the outage probability of the DF scheme is lower than that in the AF scheme for two-way relay in FD mode [33]. In other words, the FD technique is not always the best choice in outage probability because of the existence of RSI. Therefore, we propose an adaptive AF/DF selection with FD/HD switching. Due to the computational analogous of nodes A and B, we will only present the outage probability of node A.

A. OUTAGE PROBABILITY OF ADAPTIVE AF/DF SELECTION SCHEME IN FD MODE

In the adaptive FD scheme, node C attempts to decode the two-way signals firstly. If it fails, node C will switch to AF scheme.

Theorem 1: The outage probability of node A for the adaptive AF/DF selection for two-way relay in FD mode is given by

$$p_{out-A}^{FD-adapt} = p_{out-A}^{FDDF} + \frac{\lambda_1 e^{-\frac{\lambda_2 t_1 l_1}{P}}}{\lambda_1+\lambda_2 l_1} e^{-(\lambda_1+\lambda_2 l_1)x_1} - \frac{\lambda_1 l_1 e^{-\frac{\lambda_2 t_1}{P}}}{\lambda_2+\lambda_1 l_1} e^{-(\lambda_1+\frac{\lambda_2}{l_1})x_2} - \lambda_1 e^{-\frac{(2\lambda_1+\lambda_2)t_1 l_1}{P}} \times \left\{H_1\left(x_2 - \frac{2t_1 l_1}{P}\right) - H_1\left(x_1 - \frac{2t_1 l_1}{P}\right)\right\}, \quad (23)$$

where $H_1(x)$ can be written as

$$H_1(x) = e^{-\lambda_1 c_1 - \frac{\lambda_2 t_1^2 l_1 (2l_1+1)}{P^2 c_1}} - \left(\lambda_1 - \frac{\lambda_2 t_1^2 l_1 (2l_1+1)}{P^2 c_1^2}\right) e^{-\lambda_1 c_1 - \frac{\lambda_2 t_1^2 l_1 (2l_1+1)}{P^2 c_1}} \frac{(x-c_1)^2}{2} + \left\{\left(\lambda_1 - \frac{\lambda_2 t_1^2 l_1 (2l_1+1)}{P^2 c_1^2}\right)^2 - \frac{2\lambda_2 t_1^2 l_1 (2l_1+1)}{P^2 c_1^3}\right\} \times e^{-\lambda_1 c_1 - \frac{\lambda_2 t_1^2 l_1 (2l_1+1)}{P^2 c_1^2}} \frac{(x-c_1)^3}{6}. \tag{24}$$

and $c_1 = \frac{x_1+x_2}{2} - \frac{2t_1 l_1}{P}$. The abscissae of the intersection points x_1 and x_2 are respectively expressed as

$$x_1 = \frac{t_1(2l_1+1)}{P} \tag{25}$$

$$x_2 = \frac{t_1 l_1 (3 + l_1 + \sqrt{(l_1+1)(l_1+5)})}{2P} \tag{26}$$

Proof: See Appendix C.

B. OUTAGE PROBABILITY OF ADAPTIVE AF/DF SELECTION SCHEME IN HD MODE

In the adaptive HD scheme, the relaying process is similar to that in the adaptive FD scheme. Node C attempts to decode the two-way signals firstly. If it fails to decode, node C will switch to AF scheme [20].

Theorem 2: The outage probability of node A for the adaptive AF/DF selection for two-way relay in HD mode is given by

$$p_{out-A}^{HD-adapt} = p_{out-A}^{HDDF} + \frac{\lambda_1 e^{-\frac{\lambda_2 t_2 l_2}{P}}}{\lambda_1 + \lambda_2 l_2} e^{-(\lambda_1+\lambda_2 l_2)x_3} - \frac{\lambda_1 l_2 e^{-\frac{\lambda_2 t_2}{P}}}{\lambda_2 + \lambda_1 l_2} e^{-\left(\lambda_1 + \frac{\lambda_2}{l_2}\right)x_4} - \lambda_1 e^{-\frac{(2\lambda_1+\lambda_2)t_2 l_2}{P}} \times \left\{H_2\left(x_4 - \frac{2t_2 l_2}{P}\right) - H_2\left(x_3 - \frac{2t_2 l_2}{P}\right)\right\}, \tag{27}$$

where $H_2(x)$ can be written as

$$H_2(x) = e^{-\lambda_1 c_2 - \frac{\lambda_2 t_2^2 l_2 (2l_2+1)}{P^2 c_2}} - \times \left(\lambda_1 - \frac{\lambda_2 t_2^2 l_2 (2l_2+1)}{P^2 c_2^2}\right) e^{-\lambda_1 c_2 - \frac{\lambda_2 t_2^2 l_2 (2l_2+1)}{P^2 c_2}} \frac{(x-c_2)^2}{2} + \left\{\left(\lambda_1 - \frac{\lambda_2 t_2^2 l_2 (2l_2+1)}{P^2 c_2^2}\right)^2 - \frac{2\lambda_2 t_2^2 l_2 (2l_2+1)}{P^2 c_2^3}\right\} \times e^{-\lambda_1 c_2 - \frac{\lambda_2 t_2^2 l_2 (2l_2+1)}{P^2 c_2^2}} \frac{(x-c_2)^3}{6}, \tag{28}$$

and $c_2 = \frac{x_3+x_4}{2} - \frac{2t_2 l_2}{P}$. The abscissae of the intersection points x_3 and x_4 are respectively expressed as

$$x_3 = \frac{t_2(2l_2+1)}{P} \tag{29}$$

$$x_4 = \frac{t_2 l_2 (3 + l_2 + \sqrt{(l_2+1)(l_2+5)})}{2P}. \tag{30}$$

C. OUTAGE PROBABILITY OF FD/HD SWITCHING

The proposed adaptive AF/DF selection with FD/HD switching scheme is shown in Fig. 2 which always provides the best outage performance among the possible combinations of AF/DF scheme in HD/FD mode within all transmit SNR values. In this two-way relay system, node C makes the decision to choose the operating schemes by estimating the transmit SNR ($SNR = \frac{P}{\sigma^2}$). When the SNR is smaller than a threshold $\frac{2^{R_{th}}}{\xi}$, the two-way relay system chooses the adaptive FD scheme. Otherwise, it chooses the adaptive HD scheme. If it is still in outage, it chooses the DF scheme in FD mode. Below we will investigate the closed form formulas for the proposed scheme.

Theorem 3: The outage probability of node A for the adaptive AF/DF selection with FD/HD switching in two-way relay networks is given as follows.

Case 1: When $\frac{t_1 l_1}{P} \leq \frac{t_2 l_2}{P}$, i.e. $SNR \leq \frac{2^{R_{th}}}{\xi}$, the outage probability of node A for the adaptive FD/HD scheme is given by

$$p_{out-A}^{adapt} = p_{out-A}^{FD-adapt}. \tag{31}$$

Case 2: When $\frac{t_2 l_2}{P} < \frac{t_1 l_1}{P} < \min\{x_3, y_4\}$, i.e. $\frac{2^{R_{th}}}{\xi} \leq SNR \leq \min\left\{\frac{2l_2 - l_1 + 1}{\xi l_1}, \frac{l_2 - 2l_1 + 1 + \sqrt{(l_2+1)(l_2+5)}}{2\xi l_1}\right\}$, the outage probability of node A for the adaptive FD/HD scheme is given by Eq. (32), as shown at the bottom of this page, where $\hat{H}_2(x)$

$$p_{out-A}^{adapt} = p_{out-A}^{HD-adapt} - \frac{\lambda_1 e^{-\frac{\lambda_2 t_1 l_1}{P}}}{\lambda_1 + \lambda_2 l_1}\left(e^{-\frac{(\lambda_1+\lambda_2 l_1)t_1 l_1}{P}} - e^{-(\lambda_1+\lambda_2 l_1)x_5}\right) + \frac{\lambda_1 e^{-\frac{\lambda_2 t_2 l_2}{P}}}{\lambda_1 + \lambda_2 l_2}\left(e^{-\frac{(\lambda_1+\lambda_2 l_2)t_1 l_1}{P}} - e^{-(\lambda_1+\lambda_2 l_2)x_3}\right) + \lambda_1 e^{-\frac{(2\lambda_1+\lambda_2)t_2 l_2}{P}}\left\{\hat{H}_2\left(x_5 - \frac{2t_2 l_2}{P}\right) - \hat{H}_2\left(x_3 - \frac{2t_2 l_2}{P}\right)\right\} - \frac{\lambda_2 e^{-\frac{\lambda_1 t_1 l_1}{P}}}{\lambda_2 + \lambda_1 l_1}\left(e^{-\frac{(\lambda_2+\lambda_1 l_1)t_1 l_1}{P}} - e^{-(\lambda_2+\lambda_1 l_1)y_6}\right) + \frac{\lambda_2 e^{-\frac{\lambda_1 t_2 l_2}{P}}}{\lambda_2 + \lambda_1 l_2}\left(e^{-\frac{(\lambda_2+\lambda_1 l_2)t_1 l_1}{P}} - e^{-(\lambda_2+\lambda_1 l_2)y_4}\right) + \lambda_2 e^{-\frac{(\lambda_2+2\lambda_1)t_2 l_2}{P}}\left\{H_3\left(y_6 - \frac{t_2 l_2}{P}\right) - H_3\left(y_4 - \frac{t_2 l_2}{P}\right)\right\} \tag{32}$$

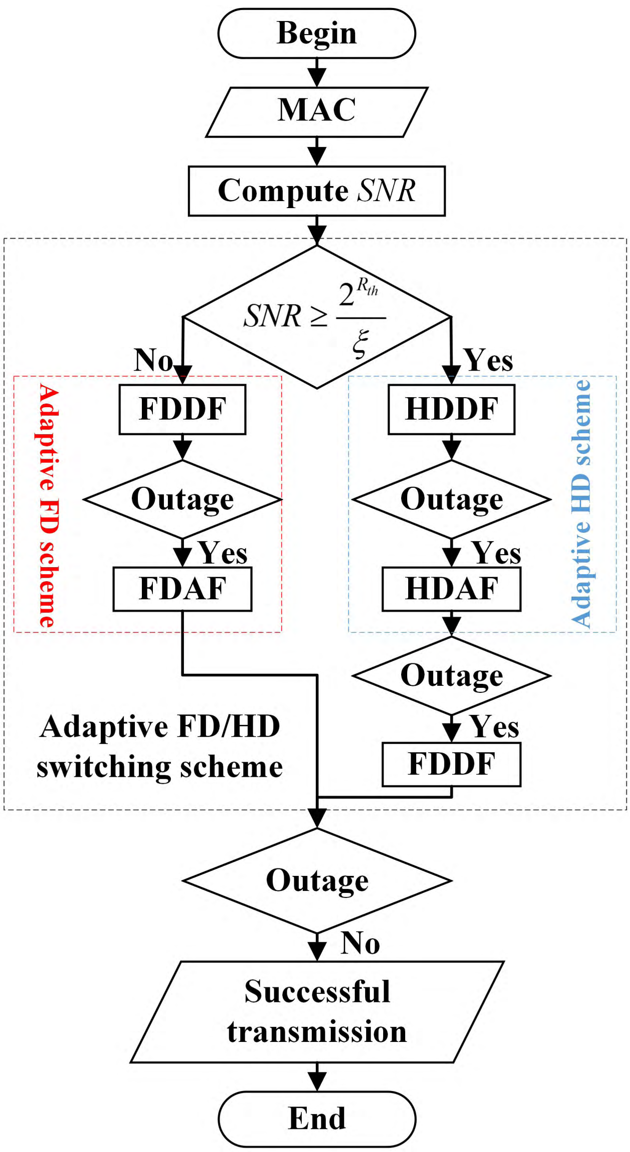

FIGURE 2. **The flow chart of the proposed adaptive AF/DF selection with FD/HD switching.**

can be written as

$$\hat{H}_2(x) = e^{-\lambda_1 \hat{c}_2 - \frac{\lambda_2 t_2^2 l_2 (2l_2+1)}{P^2 \hat{c}_2}} - \left(\lambda_1 - \frac{\lambda_2 t_2^2 l_2 (2l_2+1)}{P^2 \hat{c}_2^2}\right) e^{-\lambda_1 \hat{c}_2 - \frac{\lambda_2 t_2^2 l_2 (2l_2+1)}{P^2 \hat{c}_2}} \frac{(x-\hat{c}_2)^2}{2} + \left\{\left(\lambda_1 - \frac{\lambda_2 t_2^2 l_2 (2l_2+1)}{P^2 \hat{c}_2^2}\right)^2 - \frac{2\lambda_2 t_2^2 l_2 (2l_2+1)}{P^2 \hat{c}_2^3}\right\} \times e^{-\lambda_1 \hat{c}_2 - \frac{\lambda_2 t_2^2 l_2 (2l_2+1)}{P^2 \hat{c}_2^2}} \frac{(x-\hat{c}_2)^3}{6}, \tag{33}$$

and $\hat{c}_2 = \frac{x_3+x_5}{2} - \frac{2t_2 l_2}{P}$. The abscissa of the intersection point is expressed as

$$x_5 = \frac{2t_2 l_2 + t_2 l - t_1 + \sqrt{(2t_2 l_2 + t_2 l - t_1)^2 + 4(2t_1 t_2 l_2 + t_2^2 l)}}{2P},$$

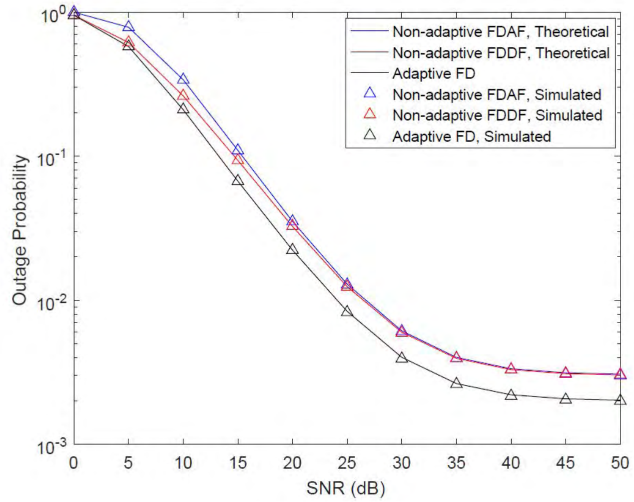

FIGURE 3. **The outage probabilities of the non-adaptive FDAF and FDDF, and adaptive FD scheme in different transmit SNRs.**

where $H_3(x)$ can be expressed as

$$H_3(x) = e^{-\lambda_2 c_3 - \frac{\lambda_1 t_2^2 l_2 (2l_2+1)}{P^2 c_3}} - \left(\lambda_1 - \frac{\lambda_1 t_2^2 l_2 (2l_2+1)}{P^2 c_3^2}\right) e^{-\lambda_2 c_3 - \frac{\lambda_1 t_2^2 l_2 (2l_2+1)}{P^2 c_3}} \frac{(x-c_3)^2}{2} + \left\{\left(\lambda_2 - \frac{\lambda_1 t_2^2 l_2 (2l_2+1)}{P^2 \hat{c}_2^2}\right)^2 - \frac{2\lambda_1 t_2^2 l_2 (2l_2+1)}{P^2 c_3^3}\right\} \times e^{-\lambda_2 c_3 - \frac{\lambda_1 t_2^2 l_2 (2l_2+1)}{P^2 c_3^2}} \frac{(x-c_3)^3}{6}, \tag{34}$$

and $c_3 = \frac{y_4+y_6}{2} - \frac{2t_2 l_2}{P}$. The abscissae of the intersection points are respectively expressed as

$$y_4 = \frac{t_2(1 + l_2 + \sqrt{(l_2+1)(l_2+5)})}{2P}$$

$$y_6 = \frac{2t_2 l + t_2 l_2 - t_1 + \sqrt{(2t_2 l + t_2 l_2 - t_1)^2 + 4(t_1 t_2 l_2 + t_2^2 l)}}{2P},$$

and where $l = l_2/l_1$.

Case 3: When $\frac{t_1 l_1}{P} \geq \max\{x_3, y_4\}$, i.e. $SNR \geq \max\left\{\frac{2l_2-l_1+1}{\xi l_1}, \frac{l_2-2l_1+1+\sqrt{(l_2+1)(l_2+5)}}{2\xi l_1}\right\}$, the outage probability of node A for the adaptive FD/HD switching scheme is given by

$$p_{out-A}^{adapt} = p_{out-A}^{HD-adapt}. \tag{35}$$

Proof: See Appendix D

V. SIMULATION RESULTS AND DISCUSSIONS

In this section, some simulation results are presented to investigate the outage performances of the proposed adaptive AF/DF selection with FD/HD switching and the conventional non-adaptive scheme. We evaluate the outage performances both in theoretical and Monte Carlo simulation results.

In Fig. 3, we consider the adaptive FD scheme. The self inference and channel coefficients are chosen as $\xi = 1 \times 10^{-3}$

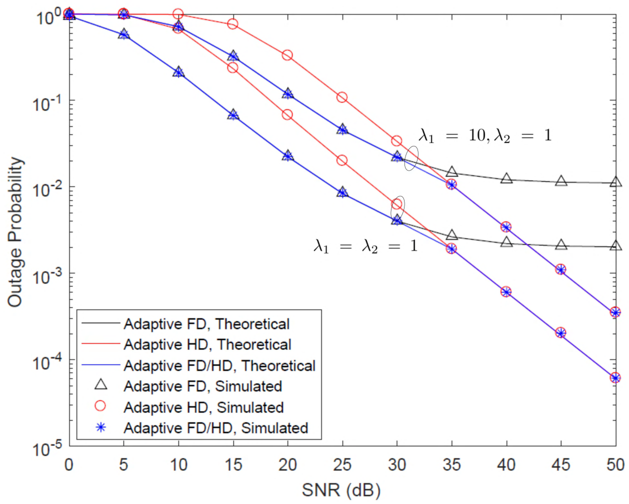

FIGURE 4. The outage probabilities of the adaptive FD, adaptive HD, and adaptive FD/HD switching scheme in different transmit SNRs.

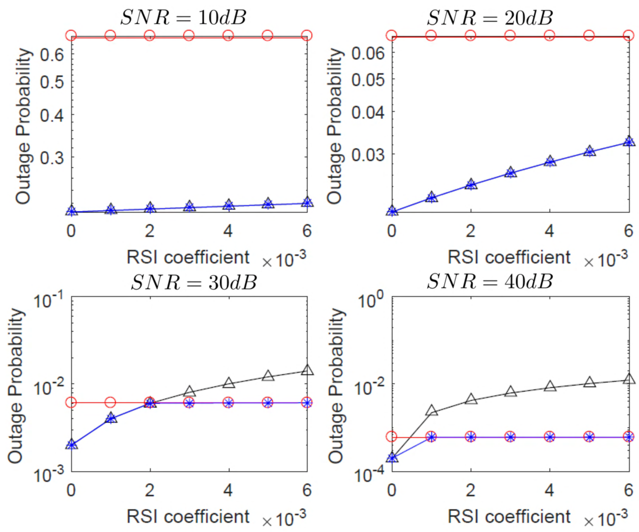

FIGURE 5. The outage probability comparisons of the adaptive FD, adaptive HD, and adaptive FD/HD switching scheme in the different RSI coefficients and transmit SNRs. (The curves and markers in this figure are consistent with these in Fig. 4).

and $\lambda_1 = \lambda_2 = 1$ respectively. The noise variances at all nodes are chosen as $\sigma^2 = 1$. The rate threshold is chosen as $R_{th} = 1b/s/Hz$. If there is no specific explanation, we will use these parameter settings below. We compare the outage probabilities of the non-adaptive FDAF and FDDF, and the adaptive FD scheme. We observe that the FDDF scheme is better than the FDAF scheme. But the outage probabilities tend to be uniform as the transmit SNR increases to infinity. Moreover, the proposed adaptive FD scheme is superior to the conventional non-adaptive AF and DF scheme in all SNR values. However, even if the adaptive FD scheme is chosen, there still exists a floor when the SNR is larger. The reason is that RSI grows with the increase of the SNR.

In Fig. 4, we consider the adaptive AF/DF selection scheme for two-way relay networks in FD and HD mode. The symmetric channel $\lambda_1 = \lambda_2 = 1$ and asymmetric channel $\lambda_1 = 10, \lambda_2 = 1$ are considered. We compare the outage probabilities of the adaptive FD and HD scheme, and the adaptive AF/DF selection scheme with FD/HD switching. It is observed that the adaptive FD scheme is better than the HD scheme when SNR is smaller. But it shows an opposite result when SNR is larger. This result indicates the adaptive FD scheme is not always the best choice despite the high spectrum efficiency. It also shows that the outage performance of the proposed adaptive AF/DF selection with FD/HD switching is the best choice compared with both the adaptive FD and HD schemes. In addition, the outage performances of all the three adaptive forwarding schemes are worse in the asymmetric channels with the higher attenuation $\lambda_1 = 10$.

In Fig. 5, we consider how the RSI coefficient ξ impacts the outage performance of the proposed adaptive AF/DF selection with FD/HD switching. The RSI coefficient is chosen as $\xi \in (0, 6 \times 10^{-3}]$. We see that outage probabilities of the adaptive AF/DF selection with FD/HD switching scheme go worse with the increase of RSI coefficient. However, they approach to a constant in the high SNR since we choose adaptive HD scheme in this case. Therefore it is not difficult to conclude that the adaptive FD scheme is the best choice with the excellent RSI cancellation technique.

VI. CONCLUSION

In this paper, we proposed an adaptive AF/DF selection with FD/HD switching to improve the outage performance for two-way relay networks. In order to obtain the optimal adaptive scheme, we first derived the closed form expressions for the non-adaptive and adaptive FD scheme. However, due to the RSI, the adaptive FD scheme is not always the best choice. Then we consider an adaptive AF/DF selection scheme in FD and HD schemes. By using this switching scheme, approximation optimal closed form formulas are obtained. The simulation results verify the correctness of theoretical derivations. It is also shown that the proposed scheme provides significant outage performance gains in all channel states and SNR values. Due to the error floor of the curves in Fig. 3 and the gain of the outage probability of adaptive FD scheme is not obvious, future work may further look into some parameters, e.g. power allocation, to increase the outage performance.

APPENDIX A
PROOF OF PROPOSITION 1

Substituting (5) to (7), the instantaneous signal to interference plus noise ratio (SINR) at node B can be expressed as

$$\gamma_B = \frac{P|\rho h_1 h_2|^2}{|\rho h_2|^2(\sigma^2 + \xi P) + \sigma^2 + \xi P} = \frac{P^2 xy}{2t_1 Py + t_1 Px + t_1^2}. \tag{36}$$

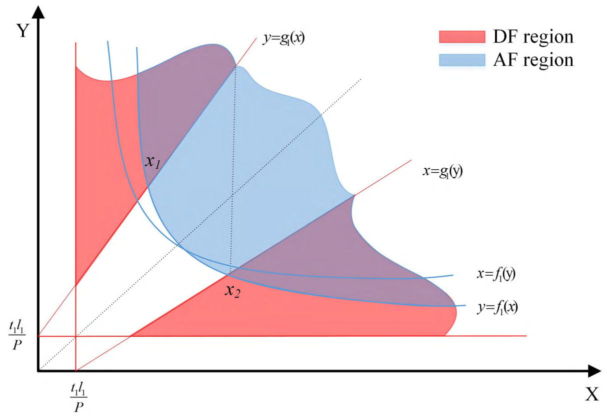

FIGURE 6. The non-outage region of the node A.

Therefore, the instantaneous rate from A to B is given by

$$R_{12}^{FDAF} = C\left(\frac{P^2xy}{2t_1Py + t_1Px + t_1^2}\right). \quad (37)$$

Similarly, the instantaneous rate from B to A is given by

$$R_{21}^{FDAF} = C\left(\frac{P^2xy}{2t_1Px + t_1Py + t_1^2}\right), \quad (38)$$

where $C(Z) = \log_2(1 + Z)$. We define two non-outage sets $\mathbf{A}_1^{FD}$ and $\mathbf{A}_2^{FD}$ that A transmits signals to B and in the reverse direction successfully relayed by C. Hence they can be respectively expressed as

$$\mathbf{A}_1^{FD} = \left\{(x, y)|R_{12}^{FDAF} \geq R_{th}\right\} = \{(x, y)|y \geq f_1(x)\} \quad (39)$$

$$\mathbf{A}_2^{FD} = \left\{(x, y)|R_{21}^{FDAF} \geq R_{th}\right\} = \{(x, y)|x \geq f_1(y)\}, \quad (40)$$

where $f_1(x) = \frac{t_1l_1Px + t_1^2l_1}{P^2x - 2t_1l_1P}$. The corresponding region of $\mathbf{A}_1^{FD}$ is the blue shadow of the Fig. 6. Next we will present the outage probability of the AF scheme for two-way relay in FD mode.

By double integral, we get the outage probability of the AF scheme for two-way relay in FD mode. The integral domain for the non-outage probability is the set $\mathbf{A}_1^{FD}$. Therefore, the outage probability of node A is derived as in (41).

$$\begin{aligned} p_{out1}^{FDAF} &= 1 - \Pr\{\mathbf{A}_1^{FD}\} \\ &= 1 - \int_{\frac{2t_1l_1}{P}}^{\infty}\int_{f_1(x)}^{\infty} f_{X,Y}(x, y)dxdy \\ &= 1 - \int_{\frac{2t_1l_1}{P}}^{\infty}\int_{\frac{t_1l_1Px + t_1^2l_1}{P^2x - 2t_1l_1P}}^{\infty} \lambda_1\lambda_2 e^{-\lambda_1x - \lambda_2y}dxdy \\ &= 1 - \int_{\frac{2t_1l_1}{P}}^{\infty} \lambda_1 e^{-\lambda_1x}\int_{\frac{t_1l_1Px + t_1^2l_1}{P^2x - 2t_1l_1P}}^{\infty} \lambda_2 e^{-\lambda_2y}dxdy \\ &= 1 - \int_{\frac{2t_1l_1}{P}}^{\infty} \lambda_1 e^{-\lambda_1x} e^{-\lambda_2\frac{t_1l_1Px + t_1^2l_1}{P^2x - 2t_1l_1P}}dx \\ &= 1 - \int_{0}^{\infty} \lambda_1 e^{-\frac{t_1l_1(2\lambda_1+\lambda_2)}{P}} e^{-\left(\lambda_1x + \frac{\lambda_2t_1^2l_1(2l_1+1)}{P^2x}\right)}dx \\ &= 1 - 2\lambda_1 e^{-\frac{t_1l_1(2\lambda_1+\lambda_2)}{P}}\sqrt{\frac{\lambda_2t_1^2l_1(2l_1+1)}{\lambda_1P^2}} \\ &\quad K_{-1}\left(\sqrt{\frac{4\lambda_1\lambda_2t_1^2l_1(2l_1+1)}{P^2}}\right). \end{aligned} \quad (41)$$

Similarly, the outage probability of node B is derived as in Eq. (42).

$$\begin{aligned} p_{out1}^{FDAF} &= 1 - \Pr\{\mathbf{A}_2^{FD}\} \\ &= 1 - 2\lambda_1 e^{-\frac{t_1l_1(2\lambda_2+\lambda_1)}{P}}\sqrt{\frac{\lambda_1t_1^2l_1(2l_1+1)}{\lambda_2P^2}} \\ &\quad \times K_{-1}\left(\sqrt{\frac{4\lambda_1\lambda_2t_1^2l_1(2l_1+1)}{P^2}}\right). \end{aligned} \quad (42)$$

The proof of the Proposition 1 is completed.

APPENDIX B
PROOF OF PROPOSITION 2

In the MAC phase, if one data stream is deemed as interference to the other, then the instantaneous rates are respectively given by

$$R_{13}^{FDWI} = C\left(\frac{P|h_1|^2}{P|h_2|^2 + \sigma^2 + \xi P}\right) \quad (43)$$

$$R_{23}^{FDWI} = C\left(\frac{P|h_2|^2}{P|h_1|^2 + \sigma^2 + \xi P}\right), \quad (44)$$

We define two non-outage sets $\mathbf{B}_1^{FD}$ and $\mathbf{B}_2^{FD}$ that node C can directly decode the signals from A and B with the other signal as interference. Hence the non-outage sets can be respectively expressed as

$$\mathbf{B}_1^{FD} = \{(x, y)|R_{13}^{FDWI} \geq R_{th}\} = \{(x, y)|x \geq g_1(y)\} \quad (45)$$

$$\mathbf{B}_2^{FD} = \{(x, y)|R_{23}^{FDWI} \geq R_{th}\} = \{(x, y)|y \geq g_1(x)\}, \quad (46)$$

where $g_1(x) = l_1x + \frac{t_1l_1}{P}$. If node C successfully decodes the signals from one node, and use the interference cancelation technique to decode the remaining signals, then the non-outage sets are respectively given by

$$\begin{aligned} \mathbf{C}_1^{FD} &= \left\{(x, y)\middle|R_{13}^{FDIC} = C\left(\frac{P|h_1|^2}{\sigma^2 + \xi P}\right) \geq R_{th}\right\} \\ &= \left\{(x, y)\middle|x \geq \frac{t_1l_1}{P}\right\} \end{aligned} \quad (47)$$

$$\begin{aligned} \mathbf{C}_2^{FD} &= \left\{(x, y)\middle|R_{13}^{FDIC} = C\left(\frac{P|h_2|^2}{\sigma^2 + \xi P}\right) \geq R_{th}\right\} \\ &= \left\{(x, y)\middle|y \geq \frac{t_1l_1}{P}\right\}, \end{aligned} \quad (48)$$

where R_{13}^{FDIC} and R_{23}^{FDIC} are the instantaneous rates after the interference cancelation from nodes B and A.

In the BC phase, node C decodes the signals and then broadcasts the recoded signal to A and B. The corresponding non-outage sets are respectively given by

$$\mathbf{D}_1^{FD} = \left\{(x,y)\middle| R_{31}^{FDDF} = C\left(\frac{P_3|h_1|^2}{\sigma_1^2+\xi_1 P_1}\right) \geq R_{th}\right\} = \left\{(x,y)\middle| x \geq \frac{t_1 l_1}{P}\right\} \tag{49}$$

$$\mathbf{D}_2^{FD} = \left\{(x,y)\middle| R_{32}^{FDDF} = C\left(\frac{P_3|h_2|^2}{\sigma_2^2+\xi_2 P_2}\right) \geq R_{th}\right\} = \left\{(x,y)\middle| y \geq \frac{t_1 l_1}{P}\right\}, \tag{50}$$

where R_{31}^{FDDF} and R_{32}^{FDDF} are respectively the instantaneous receiving rates of nodes A and B.

Since there is no outage in the transmission, node C must decode both the signals in the MAC phase and transmit the recoded signals to nodes A and B in the BC phase successfully. Therefore the non-outage sets of the whole transmission can be respectively given by

$$\mathbf{E}_1^{FD} = \left\{\left(\mathbf{B}_1^{FD}\bigcap \mathbf{C}_2^{FD}\right)\bigcup\left(\mathbf{B}_2^{FD}\bigcap \mathbf{C}_1^{FD}\right)\right\}\bigcap \mathbf{D}_2^{FD} \tag{51}$$

$$\mathbf{E}_2^{FD} = \left\{\left(\mathbf{B}_1^{FD}\bigcap \mathbf{C}_2^{FD}\right)\bigcup\left(\mathbf{B}_2^{FD}\bigcap \mathbf{C}_1^{FD}\right)\right\}\bigcap \mathbf{D}_1^{FD}. \tag{52}$$

The corresponding non-outage region is the red shadow of the Fig. 6. By double integral, we can get the outage probability of the DF scheme for two-way relay in FD mode. The integral domain for the non-outage probability is the set $\mathbf{E}_1^{FD}$. Therefore, the outage probability of node A is derived as in Eq. (53).

$$\begin{aligned} p_{out-A}^{FDDF} &= 1 - \Pr\{\mathbf{E}_1^{FD}\} \\ &= 1 - \int_{\frac{t_1 l_1}{P}}^{\infty}\int_{g_1(x)}^{\infty} f_{X,Y}(x,y)dxdy \\ &= 1 - \int_{\frac{t_1 l_1}{P}}^{\infty}\int_{l_1 x+\frac{t_1 l_1}{P}}^{\infty} \lambda_1\lambda_2 e^{-\lambda_1 x-\lambda_2 y}dxdy \\ &\quad - \int_{\frac{t_1 l_1}{P}}^{\infty}\int_{l_1 y+\frac{t_1 l_1}{P}}^{\infty} \lambda_1\lambda_2 e^{-\lambda_1 x-\lambda_2 y}dxdy \\ &= 1 - \int_{\frac{t_1 l_1}{P}}^{\infty}\lambda_1 e^{-\lambda_1 x}\int_{l_1 x+\frac{t_1 l_1}{P}}^{\infty} \lambda_2 e^{\lambda_2 y}dxdy \\ &\quad - \int_{\frac{t_1 l_1}{P}}^{\infty}\lambda_2 e^{-\lambda_1 y}\int_{l_1 y+\frac{t_1 l_1}{P}}^{\infty} \lambda_1 e^{\lambda_1 x}dxdy \\ &= 1 - \int_{\frac{t_1 l_1}{P}}^{\infty}\lambda_1 e^{-\lambda_1 x}e^{\lambda_2\left(l_1 x+\frac{t_1 l_1}{P}\right)}dx \\ &\quad - \int_{\frac{t_1 l_1}{P}}^{\infty}\lambda_2 e^{-\lambda_1 y}e^{\lambda_1\left(l_1 y+\frac{t_1 l_1}{P}\right)}dy \\ &= 1 - \frac{\lambda_1}{\lambda_1+\lambda_2 l_1}e^{-\frac{t_1 l_1(\lambda_1+\lambda_2+\lambda_2 l_1)}{P}} \\ &\quad - \frac{\lambda_2}{\lambda_2+\lambda_1 l_1}e^{-\frac{t_1 l_1(\lambda_1+\lambda_2+\lambda_1 l_1)}{P}}. \end{aligned} \tag{53}$$

Similarly, the outage probability of node B is derived as in Eq. (54).

$$\begin{aligned} p_{out-B}^{FDDF} &= 1 - \Pr\{\mathbf{E}_2^{FD}\} \\ &= 1 - \frac{\lambda_1}{\lambda_1+\lambda_2 l_1}e^{-\frac{t_1 l_1(\lambda_1+\lambda_2+\lambda_2 l_1)}{P}} \\ &\quad - \frac{\lambda_2}{\lambda_2+\lambda_1 l_1}e^{-\frac{t_1 l_1(\lambda_1+\lambda_2+\lambda_1 l_1)}{P}}. \end{aligned} \tag{54}$$

The proof of the Proposition 2 is completed.

APPENDIX C
PROOF OF THEOREM 1

In the adaptive FD scheme, node C tries to implement the DF scheme firstly. If it fails, i.e. node C can not decode both signals from A and B with the other signal as interference, node C performs the AF scheme. Therefore, the non-outage region of node A is the union set of $\mathbf{A}_1^{FD}$ and $\mathbf{E}_1^{FD}$ which is corresponding to the red and blue shadow of Fig. 6. The outage probability of node A is derived as

$$p_{out-A}^{FD-adapt} = p_{out-A}^{FDDF} - \Pr\left\{\overline{\mathbf{B}_1^{FD}}\bigcap\overline{\mathbf{B}_2^{FD}}\bigcap \mathbf{A}_1^{FD}\right\}, \tag{55}$$

where $\Pr\left\{\overline{\mathbf{B}_1^{FD}}\bigcap\overline{\mathbf{B}_2^{FD}}\bigcap \mathbf{A}_1^{FD}\right\}$ can be derived by the double integral in the region enclosed by $y = g_1(x)$, $x = g_1(y)$, and $y = f_1(x)$. Therefore they can be calculated by the expression as follows in Eq. (56), as shown at the bottom of this page, where I_1 can be expressed as

$$\begin{aligned} I_1 &= \int_{x_1}^{x_2}\lambda_1 e^{-\lambda_1 x}e^{-\lambda_2 f_1(x)}dx \\ &= \int_{x_1}^{x_2}\lambda_1 e^{-\lambda_1 x}e^{-\lambda_2\frac{t_1 l_1 Px+t_1^2 l_1}{P^2 x-2t_1 l_1 P}}dx \\ &= \int_{x_1}^{x_2}\lambda_1 e^{-\lambda_1 x}e^{-\frac{\lambda_2(2t_1^2 l_1^2+t_1^2 l_1)}{P^2 x-2t_1 l_1 P}-\frac{\lambda_2 t_1 l_1}{P}}dx \\ &= \lambda_1 e^{-\frac{(2\lambda_1+\lambda_2)t_1 l_1}{P}}\int_{x_1-\frac{2t_1 l_1}{P}}^{x_2-\frac{2t_1 l_1}{P}}\underbrace{e^{-\lambda_1 x-\frac{\lambda_2 t_1 l_1 Px+t_1^2 l_1}{P^2 x}}}_{h_1(x)}dx. \end{aligned} \tag{57}$$

$$\begin{aligned} \Pr\left\{\overline{\mathbf{B}_1^{FD}}\bigcap\overline{\mathbf{B}_2^{FD}}\bigcap \mathbf{A}_1^{FD}\right\} &= \int_{x_1}^{x_2}\int_{f_1(x)}^{g_1(x)}\lambda_1\lambda_2 e^{-\lambda_1 x-\lambda_2 y}dxdy + \int_{x_2}^{\infty}\int_{g_1^{-1}(x)}^{g_1(x)}\lambda_1\lambda_2 e^{-\lambda_1 x-\lambda_2 y}dxdy \\ &= \int_{x_1}^{x_2}\lambda_1 e^{-\lambda_1 x}\left(e^{-\lambda_2 f_1(x)} - e^{-\lambda_2 g_1(x)}\right)dx + \int_{x_2}^{\infty}\lambda_1 e^{-\lambda_1 x}\left(e^{-\lambda_2\frac{Px-t_1 l_1}{l_1 P}} - e^{-\lambda_2 g_1(x)}\right)dx \\ &= \underbrace{\int_{x_1}^{x_2}\lambda_1 e^{-\lambda_1 x}e^{-\lambda_2 f_1(x)}dx}_{I_1} - \frac{\lambda_1}{\lambda_1+\lambda_2 l_1}e^{-\frac{\lambda_2 t_1 l_1}{P}-(\lambda_1+\lambda_2 l_1)x_1} + \frac{\lambda_1 l_1}{\lambda_2+\lambda_1 l_1}e^{-\frac{\lambda_2 t_1}{P}-\left(\lambda_1+\frac{\lambda_2}{l_1}\right)x_2} \end{aligned} \tag{56}$$

As there is no closed solution of Eq. (57), we consider a second order Taylor series expansion to approach the true values. The error in this approximation is $R(n) = o[(x-c_1)^3]$. Hence $h_1(x)$ can be expressed as

$$\begin{aligned}
h_1(x) &= e^{-\lambda_1 x - \frac{\lambda_2 t_1^2 l_1(2l_1+1)}{P^2 x}} \\
&\approx \sum_{n=0}^{2} \frac{h_1^{(n)}(c_1)}{n!}(x-c_1)^n \\
&= e^{-\lambda_1 c_1 - \frac{\lambda_2 t_1^2 l_1(2l_1+1)}{P^2 c_1}} - \\
&\quad \times \left(\lambda_1 - \frac{\lambda_2 t_1^2 l_1(2l_1+1)}{P^2 c_1^2}\right) e^{-\lambda_1 c_1 - \frac{\lambda_2 t_1^2 l_1(2l_1+1)}{P^2 c_1}} (x-c_1) \\
&\quad + \left\{\left(\lambda_1 - \frac{\lambda_2 t_1^2 l_1(2l_1+1)}{P^2 c_1^2}\right)^2 - \frac{2\lambda_2 t_1^2 l_1(2l_1+1)}{P^2 c_1^3}\right\} \\
&\quad \times e^{-\lambda_1 c_1 - \frac{\lambda_2 t_1^2 l_1(2l_1+1)}{P^2 c_1^2}} \frac{(x-c_1)^2}{2},
\end{aligned} \tag{58}$$

where the convergent point for the Taylor series is chosen as $c_1 = \frac{x_1+x_2}{2} - \frac{2t_1 l_1}{P}$. Denoting $H_1(x) = \int h_1(x)dx$, then it can be expressed by

$$\begin{aligned}
&H_1(x) \\
&= \int \sum_{n=0}^{2} \frac{h_1^{(n)}(c_1)}{n!}(x-c_1)^n dx \\
&= \int \sum_{n=0}^{2} \frac{h_1^{(n)}(c_1)}{(n+1)!}(x-c_1)^{n+1} dx \\
&= e^{-\lambda_1 c_1 - \frac{\lambda_2 t_1^2 l_1(2l_1+1)}{P^2 c_1}} - \\
&\quad \left(\lambda_1 - \frac{\lambda_2 t_1^2 l_1(2l_1+1)}{P^2 c_1^2}\right) e^{-\lambda_1 c_1 - \frac{\lambda_2 t_1^2 l_1(2l_1+1)}{P^2 c_1}} \frac{(x-c_1)^2}{2} \\
&\quad + \left\{\left(\lambda_1 - \frac{\lambda_2 t_1^2 l_1(2l_1+1)}{P^2 c_1^2}\right)^2 - \frac{2\lambda_2 t_1^2 l_1(2l_1+1)}{P^2 c_1^3}\right\} \\
&\quad \times e^{-\lambda_1 c_1 - \frac{\lambda_2 t_1^2 l_1(2l_1+1)}{P^2 c_1^2}} \frac{(x-c_1)^3}{6},
\end{aligned} \tag{59}$$

Substituting Eq. (59) to Eq. (57), and then substituting Eq. (57) to Eq. (56), we can easily get the Eq. (60), as shown at the bottom of this page. Therefore, the outage probability

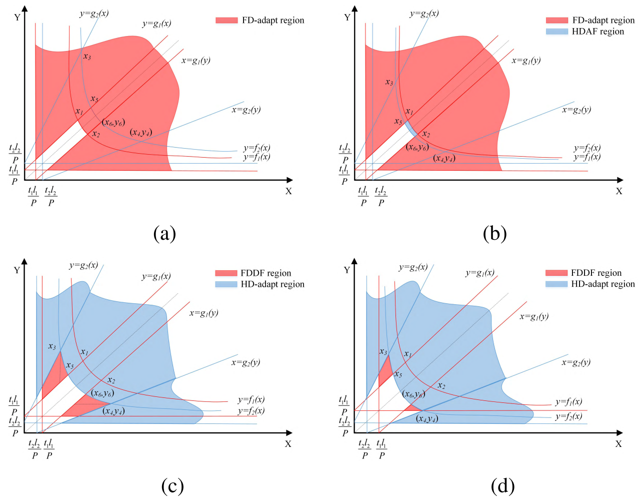

FIGURE 7. The non-outage region of node A for the adaptive AF/DF selection with FD/HD switching in two-way relay networks. (a) Case 1.1. (b) Case 1.2. (c) Case 2. (d) Case 3.

of node A can be expressed as

$$\begin{aligned}
p_{out-A}^{FD-adapt} &= p_{out-A}^{FDDF} + \frac{\lambda_1}{\lambda_1+\lambda_2 l_1} e^{-\frac{\lambda_2 t_1 l_1}{P} - (\lambda_1+\lambda_2 l_1)x_1} \\
&\quad - \frac{\lambda_1 l_1}{\lambda_2+\lambda_1 l_1} e^{-\frac{\lambda_2 t_1}{P} - \left(\lambda_1 + \frac{\lambda_2}{l_1}\right)x_2} + \lambda_1 e^{-\frac{(2\lambda_1+\lambda_2)t_1 l_1}{P}} \\
&\quad \times \left\{H_1\left(x_2 - \frac{2t_1 l_1}{P}\right) - H_1\left(x_1 - \frac{2t_1 l_1}{P}\right)\right\}.
\end{aligned} \tag{61}$$

The proof of the Theorem 1 is completed.

APPENDIX D
PROOF OF THEOREM 2

As shown in Fig. 7, the non-outage region of node A for the adaptive AF/DF selection with FD/HD switching in two-way relay networks can be classified in four cases. Since the the blue shadow region in Fig. 7(b) is too small to calculate the integral, we can ignore it and merge it to the first case. Therefore we analysis the outage probability in three cases.

Case 1: When $\frac{t_1 l_1}{P} \leq \frac{t_2 l_2}{P}$ as shown in Figs. 7(a) and 7(b), i.e. $SNR \leq \frac{2^{R_{th}}}{\xi}$, we choose the adaptive AF/DF selection scheme in FD mode. Therefore, the outage probability of node A for the adaptive FD/HD switching scheme is given by

$$p_{out-A}^{adapt} = p_{out-A}^{FD-adapt}. \tag{62}$$

$$\begin{aligned}
\Pr\left\{\overline{\mathbf{B}_1^{FD}} \bigcap \overline{\mathbf{B}_2^{FD}} \bigcap \mathbf{A}_1^{FD}\right\} &= -\frac{\lambda_1}{\lambda_1+\lambda_2 l_1} e^{-\frac{\lambda_2 t_1 l_1}{P} - (\lambda_1+\lambda_2 l_1)x_1} + \frac{\lambda_1 l_1}{\lambda_2+\lambda_1 l_1} e^{-\frac{\lambda_2 t_1}{P} - (\lambda_1+\frac{\lambda_2}{l_1})x_2} + \lambda_1 e^{-\frac{(2\lambda_1+\lambda_2)t_1 l_1}{P}} \\
&\quad \times \left\{H_1\left(x_2 - \frac{2t_1 l_1}{P}\right) - H_1\left(x_1 - \frac{2t_1 l_1}{P}\right)\right\}.
\end{aligned} \tag{60}$$

$$
\begin{aligned}
p_{out-A}^{adapt} &= p_{out-A}^{HD-adapt} - \Pr\{\overline{\mathbf{B}_1^{HD}} \bigcap \overline{\mathbf{B}_2^{HD}} \bigcap \overline{\mathbf{A}_1^{HD}} \bigcap \mathbf{E}_1^{FD}\}, \\
&= p_{out-A}^{HD-adapt} - \left(\int_{\frac{t_1 l_1}{P}}^{x_3} \int_{g_1(x)}^{g_2(x)} \lambda_1 \lambda_2 e^{-\lambda_1 x - \lambda_2 y} dxdy + \int_{x_3}^{x_5} \int_{g_1(x)}^{f_2(x)} \lambda_1 \lambda_2 e^{-\lambda_1 x - \lambda_2 y} dxdy \right) \\
&\quad - \left(\int_{\frac{t_1 l_1}{P}}^{y_4} \int_{g_1(y)}^{g_2(y)} \lambda_1 \lambda_2 e^{-\lambda_1 x - \lambda_2 y} dxdy + \int_{y_4}^{y_6} \int_{g_1(y)}^{f_2^{-1}(y)} \lambda_1 \lambda_2 e^{-\lambda_1 x - \lambda_2 y} dxdy \right) \\
&= p_{out-A}^{HD-adapt} - \frac{\lambda_1 e^{-\frac{\lambda_2 t_1 l_1}{P}}}{\lambda_1 + \lambda_2 l_1} \left(e^{-\frac{(\lambda_1 + \lambda_2 l_1) t_1 l_1}{P}} - e^{-(\lambda_1 + \lambda_2 l_1) x_5} \right) + \frac{\lambda_1 e^{-\frac{\lambda_2 t_2 l_2}{P}}}{\lambda_1 + \lambda_2 l_2} \left(e^{-\frac{(\lambda_1 + \lambda_2 l_2) t_1 l_1}{P}} - e^{-(\lambda_1 + \lambda_2 l_2) x_3} \right) \\
&\quad + \lambda_1 e^{-\frac{(2\lambda_1 + \lambda_2) t_2 l_2}{P}} \left\{ \hat{H}_2 \left(x_5 - \frac{2 t_2 l_2}{P} \right) - \hat{H}_2 \left(x_3 - \frac{2 t_2 l_2}{P} \right) \right\} - \frac{\lambda_2 e^{-\frac{\lambda_1 t_1 l_1}{P}}}{\lambda_2 + \lambda_1 l_1} \left(e^{-\frac{(\lambda_2 + \lambda_1 l_1) t_1 l_1}{P}} - e^{-(\lambda_2 + \lambda_1 l_1) y_6} \right) \\
&\quad + \frac{\lambda_2 e^{-\frac{\lambda_1 t_2 l_2}{P}}}{\lambda_2 + \lambda_1 l_2} \left(e^{-\frac{(\lambda_2 + \lambda_1 l_2) t_1 l_1}{P}} - e^{-(\lambda_2 + \lambda_1 l_2) y_4} \right) + \lambda_2 e^{-\frac{(\lambda_2 + 2\lambda_1) t_2 l_2}{P}} \left\{ H_3 \left(y_6 - \frac{t_2 l_2}{P} \right) - H_3 \left(y_4 - \frac{t_2 l_2}{P} \right) \right\},
\end{aligned}
\tag{63}
$$

Case 2: When $\frac{t_2 l_2}{P} < \frac{t_1 l_1}{P} < \min\{x_3, y_4\}$ as shown in Fig. 7(c), i.e. $\frac{2^{R_{th}}}{\xi} \leq SNR \leq \min \left\{ \frac{2l_2 - l_1 + 1}{\xi l_1}, \frac{l_2 - 2l_1 + 1 + \sqrt{(l_2+1)(l_2+5)}}{2\xi l_1} \right\}$. First we choose the adaptive AF/DF selection scheme in HD mode and then choose the DF scheme in FD mode. Similar to the proof of Theorem 1, the outage probability of node A for the adaptive FD/HD switching scheme is given by Eq. (63), as shown at the top of this page, where $\overline{\mathbf{B}_1^{HD}}$ and $\overline{\mathbf{B}_2^{HD}}$ are the outage sets that node C can not decode both the signals from A and B with the other signal as interference in the HD scheme. $\overline{\mathbf{A}_1^{HD}}$ is the outage set of node A in AF scheme for two-way relay in HD mode. $\hat{H}_2(x)$ can be expressed as in Eq. (33) and $H_3(x)$ can be expressed as in Eq. (34).

Case 3: When $\frac{t_1 l_1}{P} \geq \max\{x_3, y_4\}$ as shown in Fig. 7(d), i.e. $SNR \geq \max \left\{ \frac{2l_2 - l_1 + 1}{\xi l_1}, \frac{l_2 - 2l_1 + 1 + \sqrt{(l_2+1)(l_2+5)}}{2\xi l_1} \right\}$. Since the red shadow region is too small to calculate the integral, we ignore it and choose the adaptive AF/DF selection scheme in HD mode. Therefore, the outage probability of node A for the adaptive FD/HD switching scheme is given by

$$
p_{out-A}^{adapt} = p_{out-A}^{HD-adapt}. \tag{64}
$$

The proof of the Theorem 2 is completed.

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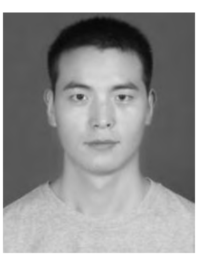

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