Paper

Outage Performance of Bidirectional Full-Duplex Amplify-and-Forward Relay Network with Transmit Antenna Selection and Maximal Ratio Combining

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Abstract—In this paper, a bidirectional full-duplex amplify-and-forward (AF) relay network with multiple antennas at source nodes is proposed. Assuming that the channel state information is known at the source nodes, transmit antenna selection and maximal ratio combining (MRC) are employed when source nodes transmit information to the relay node and receive information from the relay node respectively, in order to improve the overall signal-to-interference plus noise ratio (SINR). Analytical expressions are derived for tight upper bound SINR at the relay node and source nodes upon reception. Further, closed form expressions are also derived for end-to-end outage probability of the proposed bidirectional full-duplex AF relay network in the Nakagami-*m* fading channel environment. Although self-interference at the relay node limits the performance of the full-duplex network, the outage performance of the proposed network is better than that of conventional bidirectional full-duplex and half-duplex AF relay networks, due to the selection diversity gain in TAS and diversity and array gain in MRC.

Keywords—channel state information, Nakagami-m fading channel, self interference, SINR.

1. Introduction

Bidirectional full-duplex relay assisted wireless networks have attracted considerable interest in the field of wireless communications due to their capability to improve network coverage, capacity, data rate and spectral efficiency [1]–[4]. Several IEEE protocol standards, such as IEEE 802.16j and LTE-A, adopted the relay technology to improve coverage and capacity [5], [6]. In a bidirectional full-duplex amplify-and-forward (AF) relay network, source nodes transmit data to the relay node and, at the same time, the relay node forwards the amplified signal back to the source nodes to utilize the spectral resources more efficiently [7]. Therefore, the data rate is doubled compared to the conventional half-duplex decode-and-forward (DF) relay network with physical-layer network coding (PLNC) for mutual data exchange [8]. However, its performance is limited mainly by self-interference due to the leakage from the full-duplex relay node transmission to its own reception.

Bidirectional relaying has become a potential candidate for sustaining the evolution of fifth generation (5G) technologies towards denser heterogeneous networks, with flexible relaying modes being studied recently [9]. There are many issues, such as synchronization and channel estimation errors, which are considered in [10]–[13]. It has been reported that the increased degree of freedom (DoF) offered by spatial domain antenna arrays of multiple input multiple output (MIMO) networks may be utilized to provide a range of new solutions for self-interference cancellation/suppression [14]. Wireless transmission and reception using multiple antennas also improves the overall signal-to-noise ratio (SNR) of the network through diversity and array gains, and, hence, provides high capacity and reliability [15], [16].

However, as the number of antennas increases, the requirement to provide expensive radio frequency chains also grows [17]. Further, designing power amplifiers with the required large linearity region is a major challenge. Transmit antenna selection (TAS) is one of the alternatives enabling to solve this problem. In TAS, the transmitter selects the best antenna based on the channel state information from the receiver, obtained through the feedback channel. Thus, it requires only one RF chain, although many cheap antenna elements are used in the network. In [18]–[21] different algorithms have been proposed for antenna selection in a one way AF relay network.

In [22] antenna selection is done at both transmitter and receiver ends of the bidirectional half-duplex MIMO AF relay network. In [23], [24], the combination of TAS and maximal ratio combining (MRC) at the receiver is used in a one-way AF relay network. In [25], the performance of a dual hop AF MIMO multi-antenna relay network with the best end-to-end antenna selection was considered and compared with the transmit beamforming MRC in [26]. In [27], a wide variety of antenna selection schemes based on low complexities are proposed for one way full-duplex relaying. In [28], source transmit antenna selection for MIMO DF relay networks is proposed based on the channel state information to maximize the diversity and joint coding for multiple relay networks.

The focus of earlier research work was on transmit antenna selection in half-duplex bidirectional wireless relay networks, self-interference is the major limiting factor in full-duplex bidirectional relay network. In this paper, a bidirectional full-duplex AF relay network with multiple antennas at source nodes is proposed. Assuming that the channel state information is known at the source nodes, TAS and MRC are employed when source nodes transmit information to the relay node and receive information from the relay node respectively, in order to improve the overall SINR.

The major contributions of this paper are:

- TAS and MRC are employed at source nodes in the proposed bidirectional full-duplex AF relay network, which maximizes the overall SINR.
- A closed form analytical expression is derived for end-to-end outage probability of the proposed network in the Nakagami-*m* fading channel environment. The Nakagami-*m* fading model represents a wide variety of realistic line of sight (LoS) and non-LoS fading channels encountered in practice. Hence, the derived analytical expression of outage probability can be used to investigate the outage characteristics under different fading severity conditions of the proposed bidirectional AF full-duplex relay network.
- The outage performance of the proposed network is also compared with a half-duplex bidirectional AF relay network with TAS and MRC in the Nakagami-*m* fading environment.

The remaining part of this paper is organized as follows. The system model of the proposed bidirectional full-duplex AF relay network is presented in Section 2. Section 3 provides the outage performance analysis of the proposed bidirectional AF relay network with TAS and MRC. Numerical results are presented in Section 4, and concluding remarks are given in Section 5.

2. System Model

A bidirectional FD AF relay network is shown in Fig. 1. The source nodes $S_j,\ j=1,2$ are equipped with N multiple antenna terminals and an intermediate FD AF relay node terminal R is equipped with two antennas, one for transmitting and the other for receiving.

Let P_s and P_r be the transmit power at source nodes S_1, S_2 and relay node R respectively.

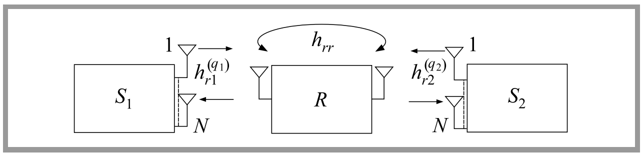

Fig. 1. System model of a bidirectional FD AF relay network.

The direct link between the source nodes does not exist due to the shadowing effect. The channel impulse response vector between source nodes S_1, S_2 and relay node R is written as $\mathbf{h}_{jr} = \left[h_{rj}^{(1)}, h_{rj}^{(2)}, \ldots, h_{rj}^{(N)}\right]^T,\ j=1,2,$ where T denotes the transpose of channel vector. Each element of the channel impulse response vector is denoted by $h_{rj}^{(l)} = \left|h_{rj}^{(l)}\right| e^{j\theta},\ l=1,2,\ldots,N,$ where $\left|h_{rj}^{(l)}\right|$ is Nakagami-*m* distributed with shape and scale parameters m, Ω and θ being uniformly distributed over $[0,\ 2\pi]$. The probability density function (PDF) of $\left|h_{rj}^{(l)}\right|$ is given by:

$$f_{\left|h_{rj}^{l}\right|}(x) = \frac{2}{\Gamma(m_l)}\left(\frac{m_l}{\Omega_l}\right)^{m_l} x^{2m_l-1}\,\mathrm{e}^{-\frac{m_l}{\Omega_l}x^2},\quad x \geq 0,\ \ l=1,2,\ldots,N, \tag{1}$$

where $\Gamma(.)$ is the Gamma function, defined as $\Gamma(\Phi) = \int_0^\infty x^{\Phi-1}e^{-\Phi}\mathrm{d}x$. The shape parameters $m_1, m_2, \ldots, m_N$ and scale parameters $\Omega_1, \Omega_2, \ldots, \Omega_N$ are independent. Nakagami-*m* fading represents a wide range of fading scenarios through its shape parameter m, which ranges from 0.5 to ∞. The $m=0.5$ represents worst-case fading and $m=\infty$, no fading. $m=1$ corresponds to Rayleigh fading. Hence, Rayleigh fading becomes a special case of the Nakagami-*m* fading channel. As m increases further, the severity of fading reduces [16]. It is assumed that channel reciprocity exists between source nodes and the relay node; then $h_{rj}^{(l)} = h_{jr}^{(l)}\ \ l=1,2,\ldots,N$ holds.

The transmit antenna selection q_j at the source nodes $S_j, j=1,2$ is based on the following criteria:

$$q_j = \underset{q\in\{1,2,\ldots,N\}}{\arg\max}\left[\left|h_{jr}^{q}\right|^2\right],\quad j=1,2. \tag{2}$$

The antenna selection information is sent to the relay node R through a dedicated control channel. In k-th time slot, the receive signal at relay node R is given by:

$$y_r(k) = \sqrt{P_s}h_{r1}^{q_1}x_1(k) + \sqrt{P_s}h_{r2}^{q_2}x_2(k) + h_{rr}t_r(k) + n_r(k). \tag{3}$$

The symbols $x_j(k),\ j=1,2$ transmitted by both source nodes $S_j,\ j=1,2$ belong to the unit symbol energies $E\left\{|x_1|^2\right\}=1$ and $E\left\{|x_2|^2\right\}=1$. The $n_r(k)$ is an additive white Gaussian noise at relay node R with zero mean and variance of σ_n^2. As the relay node R operates in a full-duplex mode, it broadcasts the receive signal at the $(k-1)$-th time slot to both the source nodes $S_j,\ j=1,2$ with an amplification factor β_r. The transmit signal $t_r(k)$ at relay node R at k-th time slot is given by:

$$t_r(k) = \sqrt{P_r}\beta_r y_r(k-1). \quad (4)$$

The self-interference h_{rr} at relay node R is also modeled as Gaussian distributed with zero mean and variance $\sigma^2_{e,r}$. Substituting Eq. (3) with Eq. (4), $t_r(k)$ can be expressed as:

$$t_r(k) = \beta_r\sqrt{P_r}\sum_{n=1}^{\infty}\left(h_{rr}\beta_r\sqrt{P_r}\right)^{n-1} g(k-n), \quad (5)$$

where $g(k) = \sqrt{P_s}h^{q_1}_{r1}x_1(k-n) + \sqrt{P_s}h^{q_2}_{r2}x_2(k-n) + n_r(k-n)$.

The variance of $t_r(k)$ is derived as:

$$\mathrm{E}\left[\left|t_r(k)\right|^2\right] = \\ = \left(P_s\left|h^{q_1}_{r1}\right|^2 + P_s\left|h^{q_2}_{r2}\right|^2 + \sigma^2_n\right)\frac{\beta^2_r P_r}{1-\left|h_{rr}\right|^2\beta^2_r P_r} = P_r. \quad (6)$$

The variance of $t_r(k)$ should be equal to P_r. Equating the right-hand side expression of Eq. (6) with P_r to prevent the oscillation at the relay node R, the amplification factor β_r of the relay node is calculated as:

$$\beta_r = \frac{1}{\sqrt{P_s\left|h^{q_1}_{r1}\right|^2 + P_s\left|h^{q_2}_{r2}\right|^2 + P_r\left|h_{rr}\right|^2 + \sigma^2_n}}. \quad (7)$$

The receive signals at l-th antenna of source nodes S_j, $j = 1,2$ are:

$$y^l_j(k) = h^l_{jr}t_r(k) + \sqrt{P_s}h^{q_j}_{jj}\delta(l-q_j)x_j(k) + n^l_j(k), \\ l = 1,2,\ldots,N, \quad j = 1,2 \quad (8)$$

where $\delta(l-q_j) = \begin{cases} 1 & \text{if } l = q_j \\ 0 & \text{if } l \neq q_j \end{cases}$.

By substituting Eq. (4) and Eq. (7) in Eq. (8), the receive signal at S_j, $j = 1,2$ by l-th antenna is expressed as:

$$\mathbf{y}^l_j(k) = \sqrt{P_rP_s}\beta_r h^l_{jr}h^{q_j}_{jr}x_j(k-1) + \\ + \sqrt{P_rP_s}\beta_r h^l_{jr}h^{q_{\bar{j}}}_{\bar{j}r}x_{\bar{j}}(k-1) + \\ + \sqrt{P_r}\beta_r h^l_{jr}h_{rr}t_r(k-1) + \\ + \sqrt{P_s}h^{q_j}_{jj}\delta(l-q_j)x_j(k) + \sqrt{P_r}\beta_r h^l_{jr}n_r(k-1) + \\ + n^l_j(k), \\ l = 1,2,\ldots,N, \; j = 1,2, \quad (9)$$

where $\{j,\bar{j}\} = \{1,2\}$ or $\{2,1\}$. In vector form, it is written as:

$$\mathbf{y}_j(k) = \sqrt{P_rP_s}\beta_r\mathbf{h}_{jr}h^{q_j}_{jr}x_j(k-1) + \\ + \sqrt{P_rP_s}\beta_r\mathbf{h}_{jr}h^{q_{\bar{j}}}_{\bar{j}r}x_{\bar{j}}(k-1) + \\ + \sqrt{P_r}\beta_r\mathbf{h}_{jr}h_{rr}t_r(k-1) + \\ + \sqrt{P_s}\mathbf{D}_{qj}\mathbf{h}_{jj}x_j(k) + \sqrt{P_r}\beta_r\mathbf{h}_{jr}n_r(k-1) + \\ + \mathbf{n}_j(k), \\ j = 1,2. \quad (10)$$

The first term in Eq. (10) is the self-information signal at the source node S_j, $j = 1,2$ and it can be subtracted. The second term is the useful signal from $S_{\bar{j}}$. The third and fourth terms are the self-interference at relay node R and source S_j respectively. The last two terms are the noise at relay node R and source node S_j. The term $\mathbf{D}_{qj}$ is a diagonal matrix in which the q_j-th diagonal element is unity. After subtracting, the self-information signal term is:

$$\mathbf{y}_j(k) = \sqrt{P_rP_s}\beta_r\mathbf{h}_{jr}h^{q_{\bar{j}}}_{\bar{j}r}x_{\bar{j}}(k-1) + \\ + \sqrt{P_r}\beta_r\mathbf{h}_{jr}h_{rr}t_r(k-1) + \\ + \sqrt{P_s}\mathbf{D}_{qj}\mathbf{h}_{jj}x_j(k) + \sqrt{P_r}\beta_r\mathbf{h}_{jr}n_r(k-1) + \\ + \mathbf{n}_j(k), \\ j = 1,2. \quad (11)$$

Since each node is equipped with multiple antennas, MRC is applied at each source node to obtain diversity gain. Now the MRC output at the source nodes S_j is expressed as:

$$z_j(k) = \mathbf{h}^*_{jr}\mathbf{y}_j(k). \quad (12)$$

Substituting Eq. (11) in Eq. (12), the MRC output is:

$$z_j(k) = \sqrt{P_rP_s}\beta_r\left\|\mathbf{h}_{jr}\right\|^2 h^{q_{\bar{j}}}_{\bar{j}r}x_{\bar{j}}(k-1) + \\ + \sqrt{P_r}\beta_r\left\|\mathbf{h}_{jr}\right\|^2 h_{rr}t_r(k-1) + \sqrt{P_s}\mathbf{D}_{qj}\mathbf{h}_{jj}x_j(k) + \\ + \sqrt{P_r}\beta_r\left\|\mathbf{h}_{jr}\right\|^2 n_r(k-1) + \mathbf{h}^*_{jr}\mathbf{n}_j(k). \quad (13)$$

Since source nodes S_j, $j = 1,2$ are ideal and non-iterative, the effect of self-interference term $\sqrt{P_s}\mathbf{D}_{qj}\mathbf{h}_{jj}x_j(k)$ is neglected. Now, the MRC output is rewritten as:

$$z_j(k) = \sqrt{P_rP_s}\beta_r\left\|\mathbf{h}_{jr}\right\|^2 h^{q_{\bar{j}}}_{\bar{j}r}x_{\bar{j}}(k-1) + \\ + \sqrt{P_r}\beta_r\left\|\mathbf{h}_{jr}\right\|^2 h_{rr}t_r(k-1) + \\ + \sqrt{P_r}\beta_r\left\|\mathbf{h}_{jr}\right\|^2 n_r(k-1) + \mathbf{h}^*_{jr}\mathbf{n}_j(k). \quad (14)$$

Given h_{jr}, the end-to-end receive SINR at each source node is:

$$\gamma_j = \frac{P_rP_s\beta^2_r\left|h^{q_{\bar{j}}}_{\bar{j}r}\right|^2\left\|\mathbf{h}_{jr}\right\|^4}{P^2_r\beta^2_r\left|h_{rr}\right|^2\left\|\mathbf{h}_{jr}\right\|^4 + P_r\beta^2_r\left\|\mathbf{h}_{jr}\right\|^4\sigma^2_n + \left\|\mathbf{h}_{jr}\right\|^2\sigma^2_n}, \\ j = 1,2. \quad (15)$$

Substituting for β_r from Eq. (7) in Eq. (15), the SINR expression is:

$$\gamma_j = \frac{P_rP_s\left|h^{q_{\bar{j}}}_{\bar{j}r}\right|^2\left|\mathbf{h}_{jr}\right|^2}{\left[\begin{array}{c} P^2_r\left|h_{rr}\right|^2\left\|\mathbf{h}_{jr}\right\|^2 + P_r\left\|\mathbf{h}_{jr}\right\|^2\sigma^2_n + P_s\left|h^{q_j}_{jr}\right|^2\sigma^2_n \\ + P_s\left|h^{q_{\bar{j}}}_{\bar{j}r}\right|^2\sigma^2_n + P_r\left|h_{rr}\right|^2\sigma^2_n + \sigma^4_n \end{array}\right]}, \\ j = 1,2. \quad (16)$$

Let $\xi_r = \frac{P_r}{\sigma^2_n}$, $\xi_s = \frac{P_s}{\sigma^2_n}$ and $\sigma^2_{e,r} = \left|h_{rr}\right|^2$. The term ξ_s denotes the SNR at source nodes, ξ_r denotes the SNR at relay and

$\sigma^2_{e,r}$ denote the variance of the self-interference at relay node R. After simple manipulations, the end-to-end receive SINR at source nodes $S_j,\ j=1,2$ is:

$$\gamma_j = \\ = \frac{\xi_s \left|h^{q_{\bar{j}}}_{\bar{j}r}\right|^2 \xi_r \left\|\mathbf{h}_{jr}\right\|^2}{\xi_r(\sigma^2_{e,r}+1)\left\|\mathbf{h}_{jr}\right\|^2+\xi_s\left(\left|h^{q_{\bar{j}}}_{\bar{j}r}\right|^2+\left|h^{q_j}_{jr}\right|^2\right)+\sigma^2_{e,r}+1}. \quad (17)$$

The variance of the self-interference $|h_{rr}|^2\xi_r$ at relay node is defined as $\sigma^2_{e,r}$. As the variances of the self-interference terms are too small, the upper bound of instantaneous SINR at the source nodes is:

$$\gamma_j < \frac{\xi_r\xi_s\left|h^{q_{\bar{j}}}_{\bar{j}r}\right|^2\left\|\mathbf{h}_{jr}\right\|^2}{\xi_r(\sigma^2_{e,r}+1)\left\|\mathbf{h}_{jr}\right\|^2+\xi_s\left|h^{q_{\bar{j}}}_{\bar{j}r}\right|^2}. \quad (18)$$

3. Performance Analysis

The overall outage probability of the proposed system occurs when γ_j falls below the threshold $\gamma\text{-th}=2^{R_t}-1$, where R_t is the required target data rate. To derive the closed form expression for overall outage probability, SINR expression is to be rewritten in a suitable form.

The upper bound of instantaneous end-to-end SINR at source nodes $S_j,\ j=1,2$:

$$\frac{1}{\gamma_j} > \frac{(\sigma^2_{e,r}+1)}{\xi_s\left|h^{q_{\bar{j}}}_{\bar{j}r}\right|^2}+\frac{1}{\xi_r\left\|h_{jr}\right\|^2}. \quad (19)$$

Further, it can be approximated as:

$$\frac{1}{\gamma_j} > \max\left\{\frac{(\sigma^2_{e,r}+1)}{\xi_s\left|h^{q_{\bar{j}}}_{\bar{j}r}\right|^2},\frac{1}{\xi_r\left\|h_{jr}\right\|^2}\right\}. \quad (20)$$

Hence, the tight upper bound of end-to-end SINR using [29] at the source nodes is:

$$\gamma_j \leq \min\left\{\frac{\xi_s\left|h^{q_{\bar{j}}}_{\bar{j}r}\right|^2}{(\sigma^2_{e,r}+1)},\xi_r\left\|\mathbf{h}_{jr}\right\|^2\right\}, \\ j=1,2. \quad (21)$$

Then, the outage probability for the proposed bidirectional AF relay network is expressed as

$$P^{s_j}_{out} = \Pr(\gamma_j < \gamma\text{-th}) \quad (22)$$

Substituting Eq. (21) in Eq. (22), the outage probability is:

$$P^{s_j}_{out} = \Pr\left[\min\left\{\frac{\xi_s\left|h^{q_{\bar{j}}}_{\bar{j}r}\right|^2}{(\sigma^2_{e,r}+1)},\xi_r\left\|\mathbf{h}_{jr}\right\|^2\right\}\leq\gamma\text{-th}\right], \\ j=1,2. \quad (23)$$

Let $P_x=\frac{\xi_s}{(\sigma^2_{e,r}+1)}$ and $P_y=\xi_r$. Equation (23) can be rewritten as:

$$P^{s_j}_{out} = \Pr\left\{\min\left\{P_x\left|h^{q_{\bar{j}}}_{\bar{j}r}\right|^2,P_y\left\|h_{jr}\right\|^2\right\}\leq\gamma\text{-th}\right\}, \\ j=1,2, \quad (24)$$

$$P^{s_j}_{out} = 1-\left(1-\Pr\left\{\left|h^{q_{\bar{j}}}_{\bar{j}r}\right|^2<\frac{\gamma\text{-th}}{P_x}\right\}\right)\times \\ \times\left(1-\Pr\left\{\left\|h_{jr}\right\|^2<\frac{\gamma\text{-th}}{P_y}\right\}\right), \\ j=1,2. \quad (25)$$

Since $\left|h^{q_{\bar{j}}}_{\bar{j}r}\right|$ is Nakagami-m, $\left|h^{q_{\bar{j}}}_{\bar{j}r}\right|^2$ follows the Gamma distribution with shape parameter $m_{q_{\bar{j}}}$ and scale parameter $\beta_{q_{\bar{j}}}=\frac{\Phi_{q_{\bar{j}}}}{m_{q_{\bar{j}}}}$, the PDF of $X=\left|h^{q_{\bar{j}}}_{\bar{j}r}\right|$ is given by:

$$f_X(x) = \frac{1}{\Gamma(m_{q_{\bar{j}}})\beta_{q_{\bar{j}}}}x^{m_{q_{\bar{j}}}-1}\,\mathrm{e}^{-\frac{x}{\beta_{q_{\bar{j}}}}}. \quad (26)$$

Similarly, $\left\|\mathbf{h}_{jr}\right\|^2=\sum_{l=1}^{N}\left|h^{l}_{jr}\right|^2$ follows the Gamma distribution with shape parameter, $l=1,2,\ldots,N$ and shape parameter $\beta_{q_{\bar{j}}}=\frac{\Phi^l_{jr}}{m^l_{jr}}$, $l=1,2,\ldots,N$, the PDF of $Y=\left\|\mathbf{h}_{jr}\right\|^2$ is given by:

$$f_Y(y) = \frac{1}{\Gamma\left(Nm^l_{jr}\right)\beta^l_{jr}}y^{Nm^l_{jr}-1}\,\mathrm{e}^{-\frac{y}{\beta^l_{jr}}}. \quad (27)$$

Substituting the Eq. (27) in Eq. (25), $\Pr\left\{\left\|h_{jr}\right\|^2<\frac{\gamma\text{-th}}{P_y}\right)$ is computed as:

$$\Pr\left\{\left\|h_{jr}\right\|^2<\frac{\gamma\text{-th}}{P_y}\right) = \\ = \int_0^{\frac{\gamma\text{-th}}{P_y}}\frac{1}{\Gamma\left(Nm^l_{jr}\right)\beta^l_{jr}}y^{Nm^l_{jr}-1}\,\mathrm{e}^{\frac{-y}{\beta^l_{jr}}}\,\mathrm{d}y = \quad (28)$$

$$= \frac{1}{\Gamma\left(Nm^l_{jr}\right)\beta^l_{jr}}\int_0^{\frac{\gamma\text{-th}}{P_y}}y^{Nm^l_{jr}-1}\,\mathrm{e}^{\frac{-y}{\beta^l_{jr}}}\,\mathrm{d}y. \quad (29)$$

The outage probability at the source nodes due to MRC is computed as [30]:

$$\Pr\left\{\left\|h_{jr}\right\|^2<\frac{\gamma\text{-th}}{P_y}\right\} = \frac{1}{\Gamma\left(Nm^l_{jr}\right)}\Gamma\left(\frac{\gamma\text{-th}}{P_y\beta^l_{jr}},Nm^l_{jr}\right). \quad (30)$$

It is worth noting that, even though a single active antenna is selected at both the source nodes, it is possible to achieve the N diversity order between the source nodes and the relay node. Similarly by using the PDF given in Eq. (26), the outage probability at the relay node is:

$$\Pr\left\{\left|h^{q_{\bar{j}}}_{\bar{j}r}\right|^2<\frac{\gamma\text{-th}}{P_x}\right\} = \left[\frac{1}{\Gamma\left(m_{q_{\bar{j}}}\right)}\Gamma\left(\frac{\gamma\text{-th}}{P_x\beta_{q_{\bar{j}}}},m_{q_{\bar{j}}}\right)\right]^N. \quad (31)$$

Substituting Eq. (30) and Eq. (31) in Eq. (25), the outage probability of the proposed system is:

$$\Pr(\gamma_j < \gamma\text{-th}) = 1 - \left\{1 - \left[\frac{1}{\Gamma\left(m_{q_{\bar{j}}}\right)}\Gamma\left(\frac{\gamma\text{-th}}{P_x \beta_{q_{\bar{j}}}}, m_{q_{\bar{j}}}\right)\right]^N\right\} \times$$
$$\times \left[1 - \frac{1}{\Gamma\left(Nm^l_{jr}\right)}\Gamma\left(\frac{\gamma\text{-th}}{P_y \beta^l_{jr}}, Nm^l_{jr}\right)\right], \quad (32)$$

where $\Gamma(\ldots)$ is the incomplete Gamma function and it is given by $\Gamma(z,\Phi) = \int_0^z x^{\Phi-1} e^{-x} \mathrm{d}x$.

4. Numerical Results and Discussions

In this section, the outage performance of the proposed bidirectional full-duplex AF relay assisted network with TAS and MRC is analyzed using the analytical expressions derived in Section 3. The parameter values for the analytical expression and simulations are based on [7] for outage analysis and are listed in Table 1.

Table 1
List of parameters

Parameters	Values
Target data rate R_t	1, 2, 4 bps/Hz
Number of antennas at source nodes N	1, 2, 4
Shape parameter m	1, 1.5, 2
Variance of channel β	2
Variance of self-interference $\sigma^2_{e,r}$	–20 to 30 dB
SNR at source nodes	0–30 dB
Relay power P_r	30 dB

The outage performance of the proposed bidirectional full-duplex AF relay network is shown in Fig. 2 at a target rate of $R_t = 4$ bps in the Nakagami-m fading environment with shape parameter $m = 1$ and for various numbers of antennas N at source nodes. At the outage probability of 10^{-1} it is observed that the minimum SNR requirement is approximately 20 dB when a single antenna $N = 1$ is employed at the source nodes. In the case of a bidirectional full-duplex (BFD) AF relay network without TAS and MRC [7], the SNR requirement is approximately 25 dB at $N = 1$. As the number of antennas N at the source nodes increases to 2, the minimum SNR requirement decreases to 14 dB. This improvement is due to the transmit diversity at the source nodes and the receive diversity and array gains at source nodes from MRC. It is observed that the analytical results precisely match exactly with the simulation results for $N \geq 2$. But, in a single antenna environment, there is a small deviation between analytical data and simulations at high SNR, due to the approximations that have been made to obtain the tight upper bound.

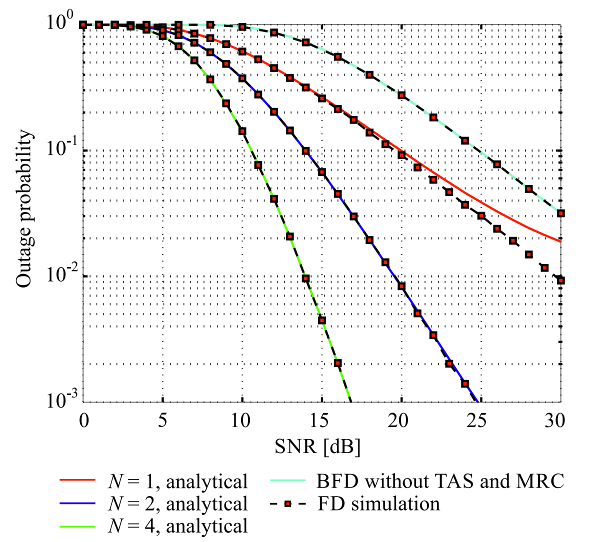

Fig. 2. Outage performance of the proposed bidirectional AF relay network in Rayleigh fading channel.

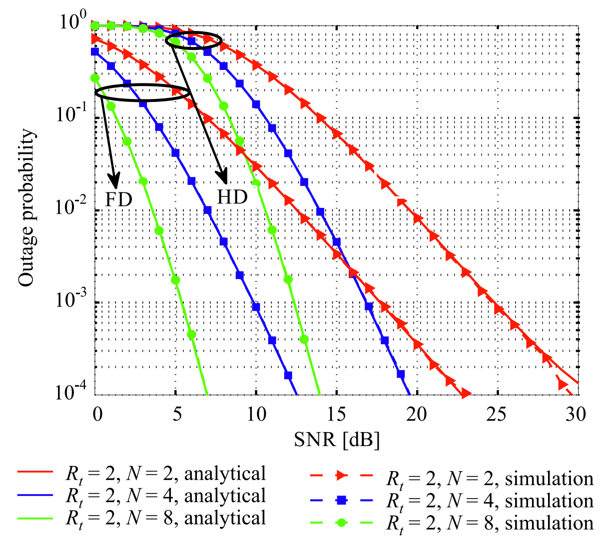

Fig. 3. Outage performance of the proposed bidirectional full-duplex AF relay network in Rayleigh fading channel and bidirectional half-duplex.

The outage performance of the proposed bidirectional full duplex AF relay network is compared with the bidirectional half-duplex AF relay network at a target rate of $R_t = 2$ bps/Hz using Fig. 3 for various numbers of antennas N at source nodes. For bidirectional half-duplex AF relay network, the outage probability expression is:

$$\Pr\left(\gamma_j < \gamma^{th}_{HD}\right) =$$
$$= 1 - \left\{1 - \left[\frac{1}{\Gamma\left(m_{q_{\bar{j}}}\right)}\Gamma\left(\frac{\gamma^{th}_{HD}}{P^{HD}_x \beta_{q_{\bar{j}}}}, m_{q_{\bar{j}}}\right)\right]^N\right\} \times$$
$$\times \left[1 - \frac{1}{\Gamma\left(Nm^l_{jr}\right)}\Gamma\left(\frac{\gamma^{th}_{HD}}{P_y \beta^l_{jr}}, Nm^l_{jr}\right)\right], \quad (33)$$

where $\gamma^{th}_{\mathrm{HD}} = 2^{2R_t} - 1$ and $P^{HD}_x = \xi_s$.

It is observed that the proposed bidirectional full-duplex AF relay network has better outage performance when compared with a half-duplex relay network. At the outage probability of 10^{-2}, the SNR requirement in a half-duplex relay network is 20 dB when $N=2$, whereas in a full duplex network it is 13 dB. With a further increase in N value to 4, the SNR requirement in half duplex decreases to 14 dB, whereas in full-duplex it falls to 7 dB.

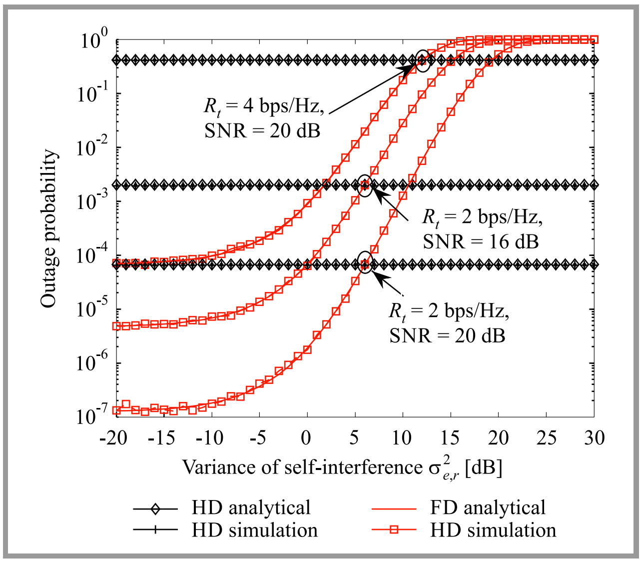

Fig. 4. Outage performance of the proposed bidirectional full-duplex AF relay network by varying the variance of the self-interference.

In Fig. 4, the effect of self-interference on the outage performance of the proposed full duplex AF relay network is examined under various target rates R_t in bps/Hz and SNR with the number of antennas at the source nodes $N = 4$. The outage probability of an FD network increases as the variance of the self interference increases. As the HD network has no effect of self-interference, its outage performance does not vary. However, the outage performance of an FD network is better than that of an HD network when the variance of self-interference $\sigma^2_{e,r}$ is very small. It is observed that the bidirectional AF FD with $R_t = 4$ bps/Hz, SNR = 20 dB and HD with $R_t = 2$ bps/Hz, SNR = 20 dB almost have the same outage performance in the case of small interference, which proves that FD is better than HD, and it doubles the rate when the self-interference is small enough.

In Fig. 5, the outage performance of the proposed bidirectional full-duplex relay network is shown for various shape parameters in the Nakagami-m fading channel. The number of antennas at the source nodes is fixed at $N = 4$ and the target rate at $R_t = 4$ bps/Hz. At an outage probability of 10^{-2}, the minimum SNR requirement of the proposed network is 14 dB when $m = 1$ (Rayleigh fading environment). When $m = 1.5$ and $m = 2$, the SNR requirement decreases to 11 dB and 9 dB respectively, as the effect of fading severity decreases.

In Fig. 6, the outage performance of the proposed bidirectional full-duplex relay network is shown for a target rate

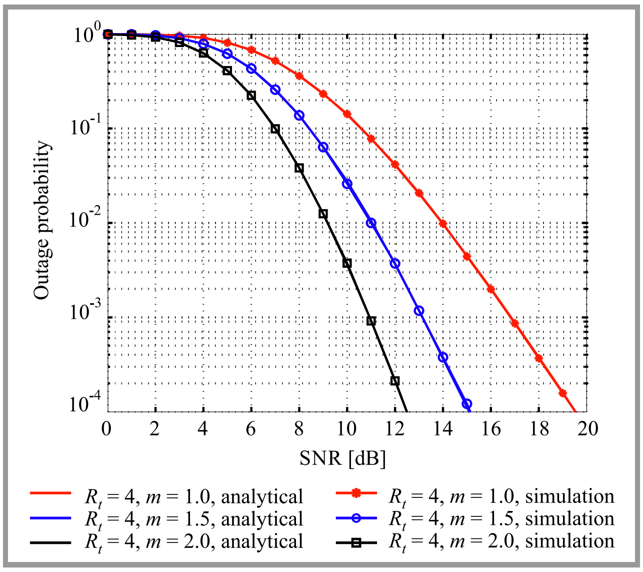

Fig. 5. Outage performance of the proposed bidirectional full-duplex relay network for different shape parameters.

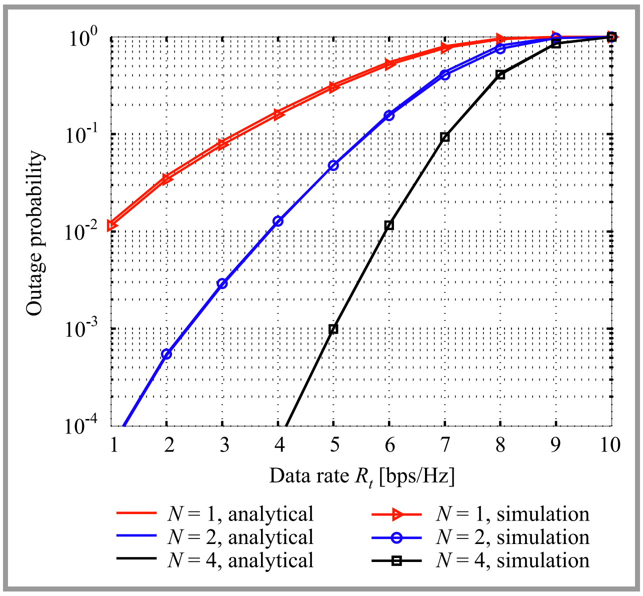

Fig. 6. Outage performance of the proposed bidirectional full-duplex relay at various data rates in Rayleigh fading channels ($m = 1$).

varying from 1 bps/Hz to and an outage probability of 10^{-3}, the data rate 10 bps/Hz. The number of antennas at source nodes is assumed to be $N=1,2,4$. For $N=2$ and an outage probability of 10^{-3}, the data rate for the proposed network is 2.5 bps/Hz, when the number of antennas N increases to 4, the same outage probability is maintained at a data rate of 5 bps/Hz. It is observed that increasing the number of antennas at the source nodes improves the data rate.

5. Conclusion

In this paper, a TAS- and MRC-based bidirectional full-duplex AF relay network is proposed to overcome the effect of self-interference at full duplex nodes and to improve the overall SINR. A closed form analytical expression is derived for the end-to-end outage probability of the proposed network in the Nakagami-*m* fading channel environment. The proposed network has better outage performance when compared with a full-duplex bidirectional AF relay network with a single antenna at the source nodes. Further, it provides better performance than a half-duplex bidirectional AF really network.

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