PERFORMANCE ANALYSIS OF FULL-DUPLEX DECODE-AND-FORWARD RELAY NETWORK WITH SPATIAL MODULATION

Nguyen Le Van[1], *Nguyen Ba Cao*[1], *Tran Xuan Nam*[1]

Abstract

In this paper, we analyze performance of the Full Duplex (FD) Decode-and-Forward relay network using Spatial Modulation (SM) technique, called SM-FD relay network, in the presence of Residual Self-Interference (RSI) due to imperfect Self-Interference Cancellation (SIC). Based on mathematical calculation, the exact expressions of Outage Probability (OP), Symbol Error Probability (SEP) and Ergodic Capacity of the SM-FD relay network is derived over Rayleigh fading channel. Impacts of RSI, number of received antennas and data transmission rate on the system performance are also investigated and compared with those of the SM Half-Duplex (SM-HD) relay network. Finally, the analytical results are validated by Monte-Carlo simulation.

Index terms

Spatial modulation (SM), full-duplex (FD), self-interference cancellation (SIC), outage probability (OP), symbol error probability (SEP), ergodic capacity.

1. Introduction

FULL-duplex (FD) communication is a promising new technique for wireless communications that may potentially double the spectral efficiency, when compared to half-duplex (HD) systems, by allowing simultaneously transmission and reception at the same frequency band and same time slot [1], [2]. However, the FD transmission produces high-power Self-Interference (SI), i.e. the interference leaking from the transmitter to the receiver within a transceiver, which reduces the capacity of FD systems [3]. Significant efforts have been made in various fields such as signal processing and antenna design for effectively suppressing this SI. The SI cancellation (SIC) techniques can be classified in three domains [1], i.e. propagation, analog and digital, to reduce the SI to an acceptable level at the receiver [4]. Therefore, FD technique can be implemented in various wireless systems such as sensor network, massive MIMO, relaying systems and possibly the future wireless networks such as the fifth generation (5G) and beyond.

Meanwhile, Spatial Modulation (SM) is an effective technique to increase the spectral efficiency of a multiple-input multiple-output (MIMO) system by using antenna indices

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as a means of information bearing. In an SM system, only one antenna is activated according to the incoming data bits to transmit an $M-$PSK/QAM symbol. The SM system uses only a single antenna for transmitting and thus can avoid Inter Channel Interference (ICI) and antenna synchronization problems as in the conventional MIMO systems [5], [6]. Therefore, SM is considered as a low-complexity, yet energy-efficient MIMO transmission technique. Moreover, SM is a MIMO technology that is inherently suitable for FD transmission, as one activated antenna is in transmission mode while the other inactive antennas can be utilized for reception. In other words, in an SM-FD system, the inactive antennas can be used to improve the spectral efficiency, as well as to receive data transmitted from other nodes. Therefore, SM for FD point-to-point transmission has been widely considered in the literature such as [2], [7], [8].

On the other hand, relaying communications is recognized by the Third Generation Partnership Projects Long Term Evolution-Advanced (3GPP LTE-A) as an effective way to enhance the coverage and achievable rate at cell edges and in hot spot areas [9]. In the context of relaying systems, SM-FD has also been considered in [10]–[14]. Specifically, in [13], the lower and upper bounds of the outage probability (OP) of the SM-MIMO system with decode-and-forward (DF) FD relay were derived over cascaded $\alpha-\mu$ fading channels. It also demonstrated that the RSI had a strong impact on the OP performance of the system. The work in [14] considered the SM-MIMO system with amplify-and-forward (AF) FD/HD relaying. It successfully derived a new unified tight upper-bound of the bit error rate (BER) of the system. The results of the paper indicate that the SM-MIMO-FD relay system can improve the BER and the spectral efficiency if suitable SIC techniques are applied. Under the same assumption of the RSI, authors in [10]–[12] investigated the SM-MIMO-FD relay systems which can exploit the benefits of the FD transmission mode. The approximate expressions of SEP [12] and BER [10], [11] were also derived for performance evaluation.

Although the previous works conducted various performance analyses, their results were limited to either upper and lower bounds or approximate expressions but not the exact closed-form expressions of SEP and BER. Therefore, it is required to have exact mathematical expressions for the performance evaluation rather than the upper bound or approximate ones for better understanding the system behaviors. Motivated by this problem, in this paper, we aim to introduce an exact mathematical framework for computing the OP, SEP and ergodic capacity of the SM-FD relay system with DF protocol applied at the relay. The main contributions of this paper can be summarized as follows:

- We analyze the SM-MIMO-FD relay system where SM is used at the source and relay nodes under the impact of the RSI caused by the imperfect SIC. The exact closed-form expressions of OP, SEP and ergodic capacity for the system over the Rayleigh fading channel is derived.
- We investigate the impact of RSI, number of reception antennas and data transmission rate on the system performance of the SM-FD relay system and compare them with those of the SM-HD relay system. The investigated results show that

when $\tilde{\Omega} < -10$ dB, the SM-FD relay system attains higher capacity than the SM-HD relay one with an acceptable performance degradation at low SNR regime. However, when the RSI is large ($\tilde{\Omega} = 0$ dB), the capacity of the SM-FD relay system is not significantly larger than the SM-HD relay at very low SNR regime while the SEP performance is much lower than the SM-HD relay system. Finally, the analytical results are validated by Monte-Carlo simulations.

The rest of this paper is organized as follows. Section 2 presents the system model. Section 3 provides the detailed derivations of the closed-form expression of OP, SEP and ergodic capacity. Numerical results and performance evaluations are provided in Section 4. Finally, Section 5 draws the conclusion of the paper.

2. System Model

The block diagram of the considered SM-FD relay system is shown in Fig. *1*. The information is transferred from a source node S to a destination node D via a relay node R. All of the three node are MIMO devices in which S and D operate in the half-duplex (HD) mode with N_t^{S} transmission antennas at S and N_r^{D} receiving antennas at D, while the one-way DF relay node operates in the FD mode with N_t^{R} transmission antennas and N_r^{R} reception antennas. Noted that the relay node can used shared-antennas to transmit and receive signals simultaneously. However, using separate antennas has been proved to obtain better SI suprression [15], [16]. The SM technique is used at both node S and R.

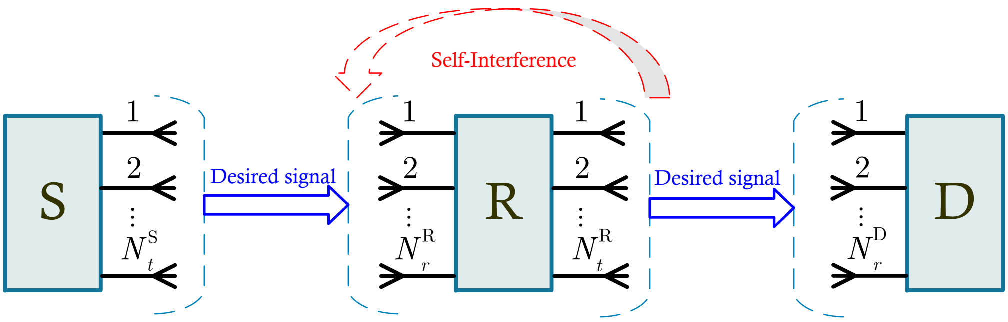

Fig. 1. Block diagram of the SM-FD relay system with self-interference.

At time slot t, the received signal at R can be calculated as follows:

$$\mathbf{y}_{\mathrm{R}}(t) = \sqrt{P_{\mathrm{S}}}\mathbf{h}_i^{\mathrm{R}} x_{\mathrm{S}}(t) + \sqrt{P_{\mathrm{R}}}\mathbf{h}_j^{\mathrm{R}} x_{\mathrm{R}}(t) + \mathbf{z}_{\mathrm{R}}(t), \tag{1}$$

where x_{S} and x_{R} are the transmitted signals from the i-th activated antenna of S and the j-th activated antenna of R, respectively ($i \in \{1, 2, \ldots, N_t^{\mathrm{S}}$, $j \in \{1, 2, \ldots, N_t^{\mathrm{R}}$); P_{S} and P_{R} are respectively the average transmission powers at S and R; $\mathbf{h}_i^{\mathrm{R}}$ is the channel vector from the i-th transmit antenna of S to N_r^{R} receive antennas of R, $\mathbf{h}_j^{\mathrm{R}}$ is the SI channel vector from the j-th transmit antenna of R to its N_r^{R} receive antennas. These channels are assumed to undergo flat Rayleigh fading, which can be modeled by independent and identically distributed complex Gaussian random variables with zero mean and unit variance. $\mathbf{z}_{\mathrm{R}}$ is the noise vector whose elements are modeled by a complex Gaussian random variable with zero-mean and variance of σ^2.

At the FD relay, we assume that the transmit and receive antennas are both directional, thus there will be no direct link which causes the self-interference (SI) from the transmit to the receive antenna. This SI is mainly due to reflections caused by multipath propagation. We also assume that the system can use all SIC techniques in the three domains, i.e., propagation, analog, and digital domain, to remove the SI [17], [18]. After all these SIC techniques, the relay node can achieve up to 110 dB SI suppression [19]. Moreover, since the SI is canceled from the received signal in the analog and digital domain by reconstructing the SI signal, the RSI is in fact the resulted errors due to the imperfect reconstruction, or more correctly, the imperfect SI channel estimation. Moreover, as the digital-domain cancellation is done after a quantization operation, RSI at the relay $\mathbf{r}_{\mathrm{SI}}$ can be modeled using complex Gaussian random variable [11], [18]–[20] with zero mean and variance of σ^2_{RSI}, i.e. $\sigma^2_{\mathrm{RSI}} = \tilde{\Omega} P_{\mathrm{R}}$ where $\tilde{\Omega}$ denotes the SIC capability at the relay.

Therefore, the received signal at R after SIC can be rewritten from (1) as

$$\mathbf{y}_{\mathrm{R}}(t) = \sqrt{P_{\mathrm{S}}}\mathbf{h}^{\mathrm{R}}_i x_{\mathrm{S}}(t) + \mathbf{r}_{\mathrm{SI}}(t) + \mathbf{z}_{\mathrm{R}}(t), \tag{2}$$

and the received signal at the destination D is then given by

$$\mathbf{y}_{\mathrm{D}}(t) = \sqrt{P_{\mathrm{R}}}\mathbf{h}^{\mathrm{D}}_j x_{\mathrm{R}}(t) + \mathbf{z}_{\mathrm{D}}(t), \tag{3}$$

where $\mathbf{h}^{\mathrm{D}}_j$ is the channel vector from the j-th transmit antenna of R to N^{D}_r receiving antennas of D; $\mathbf{z}_{\mathrm{D}}$ is the AWGN noise vector at D.

At the receiver side, the maximal ratio combining (MRC) is used to coherently combine the signals from N_r receive antennas. Then in order to recover the transmitted bits, the receiver can use the joint ML detection for estimating both the activated transmit antenna index and the M-ary modulated symbols. In this paper, as we are interested in analyzing the impact of the RSI due to the FD mode on the system performance, we assume that the receivers of both R and D can perfectly estimate the activated antenna indices of the respective transmitters for the ML detection [13], [21]

From (2) and (3), the instantaneous signal-to-interference-plus-noise-ratios (SINRs) of $\mathrm{S}-\mathrm{R}$ and $\mathrm{R}-\mathrm{D}$ links can be given as follows

$$\gamma_{\mathrm{R}} = \frac{P_{\mathrm{S}}\|\mathbf{h}^{\mathrm{R}}_i\|^2}{\sigma^2_{\mathrm{RSI}} + \sigma^2} = \|\mathbf{h}^{\mathrm{R}}_i\|^2 \bar{\gamma}_{\mathrm{R}}, \tag{4}$$

$$\gamma_{\mathrm{D}} = \frac{P_{\mathrm{R}}\|\mathbf{h}^{\mathrm{D}}_j\|^2}{\sigma^2} = \|\mathbf{h}^{\mathrm{D}}_j\|^2 \bar{\gamma}_{\mathrm{D}}, \tag{5}$$

where $\bar{\gamma}_{\mathrm{R}} = \frac{P_{\mathrm{S}}}{\sigma^2_{\mathrm{RSI}}+\sigma^2}$ and $\bar{\gamma}_{\mathrm{D}} = \frac{P_{\mathrm{R}}}{\sigma^2}$ denote the average SINR at R and the average signal-to-noise-ratio (SNR) at D, respectively.

Since the relay node uses the DF protocol, the instantaneous end-to-end SINR of the considered system is defined as

$$\gamma_{\mathrm{e2e}} = \min(\gamma_{\mathrm{R}}, \gamma_{\mathrm{D}}). \tag{6}$$

where γ_{R} and γ_{D} are respectively the instantaneous SINRs at R and D.

3. Performance Analysis

In this section, we derive the exact closed-form expression for the OP and then obtain the SEP and ergodic capacity of the considered SM-FD relay system.

3.1. Outage probability

Denote the minimum data trasmission rate of the $\mathrm{S-R}$ and $\mathrm{R-D}$ links respectively $\mathcal{R}_0^1$ and $\mathcal{R}_0^2$. For the derivation convenience, assumed that $\mathcal{R}_0^1 = \mathcal{R}_0^2 = \mathcal{R}_0$ and both S and R have the same N_t transmitting antennas for the same expected spectral efficiency.

For the considered SM-FD relay system, the data bits are conveyed not only by the modulated symbol but also by the index of the activated antenna element. Therefore, the data rate of the considered system can be calculated as follows [13], [21]

$$\mathcal{R}_{\mathrm{SM}} = \log_2(N_t) + \log_2(1+\gamma_{\mathrm{e2e}}), \tag{7}$$

where N_t is the number of transmission antennas at the transmiter $(\mathrm{S}$ or $\mathrm{R})$; γ_{e2e} is the instantaneous end-to-end SINR of the system. Note that the term $\log_2(N_t)$ denotes the data rate obtained by the SM technique.

In the case of perfect antenna index estimation, the OP of the considered system is defined as follows [13], [21]:

$$\begin{aligned}\mathcal{P}_{\mathrm{out}} &= \Pr\{\log_2(N_t) + \log_2(1+\gamma_{\mathrm{e2e}}) < \mathcal{R}_0\},\\ &= \Pr\left\{\gamma_{\mathrm{e2e}} < 2^{\mathcal{R}} - 1\right\},\end{aligned} \tag{8}$$

where $\mathcal{R} = \mathcal{R}_0 - \log_2(N_t)$ is the data rate obtained by the modulation scheme.

Denote the threshold by $\gamma_{\mathrm{th}} = 2^{\mathcal{R}} - 1$. From (8), we obtain the OP of the SM-FD relay system in Theorem 1 below.

Theorem 1: The OP of the SM-FD relay system over the Rayleigh fading channel in the presence of RSI are given by

$$\mathcal{P}_{\mathrm{out}} = 1 - e^{-\frac{\gamma_{\mathrm{th}}}{\bar{\gamma}_{\mathrm{R}}} - \frac{\gamma_{\mathrm{th}}}{\bar{\gamma}_{\mathrm{D}}}} \sum_{l=0}^{N_r^{\mathrm{R}}-1} \sum_{m=0}^{N_r^{\mathrm{D}}-1} \frac{1}{l!m!} \frac{(\gamma_{\mathrm{th}})^{l+m}}{\bar{\gamma}_{\mathrm{R}}^l \bar{\gamma}_{\mathrm{D}}^m}, \tag{9}$$

where $\bar{\gamma}_{\mathrm{R}}$ and $\bar{\gamma}_{\mathrm{D}}$ are the average SINR of R and D respectively.

Proof: From (8), the OP of the SM-FD relay system is expressed as

$$\begin{aligned}\mathcal{P}_{\text{out}} &= \Pr\left\{\gamma_{\text{e2e}} < \gamma_{\text{th}}\right\} = \Pr\left\{\min\{\gamma_{\text{R}},\gamma_{\text{D}}\} < \gamma_{\text{th}}\right\} \\ &= \Pr\left\{(\gamma_{\text{R}} < \gamma_{\text{th}}) \cup (\gamma_{\text{D}} < \gamma_{\text{th}})\right\}. \end{aligned} \tag{10}$$

Using the probability law of two independent variables $\mathcal{A}$ and $\mathcal{B}$ [22], i.e. $\Pr\{\mathcal{A}\cup\mathcal{B}\} = \Pr\{\mathcal{A}\} + \Pr\{\mathcal{B}\} - \Pr\{\mathcal{A}\}\Pr\{\mathcal{B}\}$, we have

$$\mathcal{P}_{\text{out}} = \Pr\{\gamma_{\text{R}} < \gamma_{\text{th}}\} + \Pr\{\gamma_{\text{D}} < \gamma_{\text{th}}\} - \Pr\{\gamma_{\text{R}} < \gamma_{\text{th}}\}\Pr\{\gamma_{\text{D}} < \gamma_{\text{th}}\}. \tag{11}$$

To calculate OP in (11), we first start with the cummulative distribution function (CDF) and probability distribution function (PDF) of the channel gain which follows Rayleigh fading distribution, i.e.,

$$F_{|h|^2}(x) = \Pr\{|h|^2 < x\} = 1 - \exp\left(-\frac{x}{\Omega}\right), x \geq 0, \tag{12}$$

$$f_{|h|^2}(x) = \frac{1}{\Omega}\exp\left(-\frac{x}{\Omega}\right), x \geq 0, \tag{13}$$

where $\Omega = \mathbb{E}\{|h|^2\}$ is the average channel gain; $\mathbb{E}$ denotes the expectation operator. In this paper, for ease of presentation, $\Omega = 1$ is assumed for all channel gains.

Applying (4) and (5) to compute the probability in (11) as

$$\begin{aligned}\Pr\left\{\gamma_{\text{R}} < \gamma_{\text{th}}\right\} &= \Pr\left\{\left\|\mathbf{h}_i^{\text{R}}\right\|^2\bar{\gamma}_{\text{R}} < \gamma_{\text{th}}\right\} \\ &= \Pr\left\{\left\|\mathbf{h}_i^{\text{R}}\right\|^2 < \frac{\gamma_{\text{th}}}{\bar{\gamma}_{\text{R}}}\right\}. \end{aligned} \tag{14}$$

Based on (12) with the summation of channel gains $\left\|\mathbf{h}_i^{\text{R}}\right\|^2 = \sum_{l=1}^{N_r^{\text{R}}} |h_{il}|^2$, the probability in (14) is calculated as

$$\Pr\{\gamma_{\text{R}} < x\} = 1 - e^{-\frac{\gamma_{\text{th}}}{\bar{\gamma}_{\text{R}}}} \sum_{l=0}^{N_r^{\text{R}}-1} \frac{1}{l!}\left(\frac{\gamma_{\text{th}}}{\bar{\gamma}_{\text{R}}}\right)^l. \tag{15}$$

Similarly, the $\Pr\{\gamma_{\text{D}} < x\}$ is given by

$$\Pr\{\gamma_{\text{D}} < \gamma_{\text{th}}\} = 1 - e^{-\frac{\gamma_{\text{th}}}{\bar{\gamma}_{\text{D}}}} \sum_{m=0}^{N_r^{\text{D}}-1} \frac{1}{m!}\left(\frac{\gamma_{\text{th}}}{\bar{\gamma}_{\text{D}}}\right)^m. \tag{16}$$

Substituting (15) and (16) into (11), we obtain the OP expression of the system as in (9) of Theorem 1.

3.2. Symbol Error Probability

For a SM-FD relay system, the SEP can be defined as [23]

$$\mathrm{SEP} = a\mathbb{E}\{Q(\sqrt{b\gamma_{\mathrm{e2e}}})\} = \frac{a}{\sqrt{2\pi}} \int_0^\infty F_{\gamma_{\mathrm{e2e}}}\left(\frac{t^2}{b}\right) e^{-\frac{t^2}{2}} dt, \tag{17}$$

where a and b are constants and their values depend on the modulation types, e.g. $a = 1, b = 2$ for the binary phase-shift keying (BPSK) modulation [23]. The values of a and b are determined using Table 6.1 of [23]; $Q(x)$ denotes the Gaussian function; γ_{e2e} is the instantaneous end-to-end SINR of the considered system which is determined in (6); $F_{\gamma_{\mathrm{e2e}}}(.)$ is CDF of γ_{e2e} [24], [25]. Let $x = \frac{t^2}{b}$, then (17) becomes

$$\mathrm{SEP} = \frac{a\sqrt{b}}{2\sqrt{2\pi}} \int_0^\infty \frac{e^{-bx/2}}{\sqrt{x}} F_{\gamma_{\mathrm{e2e}}}(x) dx. \tag{18}$$

From (18), we derive the SEP of the SM-FD relay system in Theorem 2 given below.

Theorem 2: The SEP of the SM-FD relay system over the Rayleigh fading channel in the presence of RSI is given as follows

$$\mathrm{SEP} = \frac{a}{2} - \frac{a\sqrt{b}}{2\sqrt{2\pi}} \sum_{l=0}^{N_r^{\mathrm{R}}-1} \sum_{m=0}^{N_r^{D}-1} \frac{\Gamma\left(l+m+\frac{1}{2}\right)}{l!m!\bar{\gamma}_{\mathrm{R}}^l \bar{\gamma}_{\mathrm{D}}^m \left(\frac{1}{\bar{\gamma}_{\mathrm{R}}} + \frac{1}{\bar{\gamma}_{\mathrm{D}}} + \frac{b}{2}\right)^{l+m+\frac{1}{2}}}, \tag{19}$$

where $\Gamma(\cdot)$ is Gamma function [26], a and b are constants whose values depend on the modulation types [23].

Proof: To calculate SEP of the system, we start with the definition of the CDF of the SINR, i.e.,

$$F_{\gamma_{\mathrm{e2e}}}(x) = \Pr\{\gamma_{\mathrm{e2e}} < x\}. \tag{20}$$

Replacing γ_{th} in the OP expression given in (9) by x, the CDF in (20) is given by

$$F_{\gamma_{\mathrm{e2e}}}(x) = 1 - e^{-\frac{x}{\bar{\gamma}_{\mathrm{R}}} - \frac{x}{\bar{\gamma}_{\mathrm{D}}}} \sum_{l=0}^{N_r^{\mathrm{R}}-1} \sum_{m=0}^{N_r^{\mathrm{D}}-1} \frac{1}{l!m!} \frac{(x)^{l+m}}{\bar{\gamma}_{\mathrm{R}}^l \bar{\gamma}_{\mathrm{D}}^m}, \tag{21}$$

Substitute (21) into (18), the SEP of the system is obtained as

$$\begin{aligned}
\mathrm{SEP} =& \frac{a\sqrt{b}}{2\sqrt{2\pi}} \int_0^\infty \frac{e^{-bx/2}}{\sqrt{x}} \left[1 - e^{-\frac{x}{\bar{\gamma}_{\mathrm{R}}} - \frac{x}{\bar{\gamma}_{\mathrm{D}}}} \sum_{l=0}^{N_r^{\mathrm{R}}-1} \sum_{m=0}^{N_r^{\mathrm{D}}-1} \frac{1}{l!m!} \frac{(x)^{l+m}}{\bar{\gamma}_{\mathrm{R}}^l \bar{\gamma}_{\mathrm{D}}^m}\right] dx \\
=& \frac{a\sqrt{b}}{2\sqrt{2\pi}} \left[\int_0^\infty \frac{e^{-bx/2}}{\sqrt{x}} dx - \sum_{l=0}^{N_r^{\mathrm{R}}-1} \sum_{m=0}^{N_r^{\mathrm{D}}-1} \frac{1}{l!m!\bar{\gamma}_{\mathrm{R}}^l \bar{\gamma}_{\mathrm{D}}^m} \int_0^\infty x^{l+m-\frac{1}{2}} e^{-x\left(\frac{1}{\bar{\gamma}_{\mathrm{R}}} + \frac{1}{\bar{\gamma}_{\mathrm{D}}} + \frac{b}{2}\right)} dx\right].
\end{aligned} \tag{22}$$

Applying eq.(3.361.2) and eq.(3.381.4) in [26] to solve the first and second intergrals in (22) respectively, we derive the SEP expression of the SM-FD relay system as in (19) of Theorem 2.

3.3. Ergodic capacity

The ergodic capacity of the SM-FD relay system is determined by [23], [27], [28]:

$$C = \mathbb{E}\left\{\log_2(1+\gamma_{\mathrm{e2e}})\right\} = \frac{1}{\ln 2}\int_0^{\infty} \frac{1 - F_{\gamma_{\mathrm{e2e}}}(x)}{1+x}dx. \tag{23}$$

From (23), ergodic capacity of the SM-FD relay system is derived as in Theorem 3 given below.

Theorem 3: Ergodic capacity of the SM-FD relay system is given as

$$\begin{aligned} C =& \frac{1}{\ln 2}\sum_{l=0}^{N_r^{\mathrm{R}}-1}\sum_{m=0}^{N_r^{\mathrm{D}}-1} \frac{(-1)^{l+m-1}}{l!m!\bar{\gamma}_{\mathrm{R}}^{l}\bar{\gamma}_{\mathrm{D}}^{m}} e^{\frac{1}{\bar{\gamma}_{\mathrm{R}}}+\frac{1}{\bar{\gamma}_{\mathrm{D}}}} \mathrm{Ei}\left(-\frac{1}{\bar{\gamma}_{\mathrm{R}}}-\frac{1}{\bar{\gamma}_{\mathrm{D}}}\right) \\ &+ \frac{1}{\ln 2}\sum_{l=0}^{N_r^{\mathrm{R}}-1}\sum_{m=0}^{N_r^{\mathrm{D}}-1}\sum_{k=1}^{l+m} \frac{(-1)^{l+m-k}(k-1)!}{l!m!\bar{\gamma}_{\mathrm{R}}^{l}\bar{\gamma}_{\mathrm{D}}^{m}} \left(\frac{1}{\bar{\gamma}_{\mathrm{R}}}+\frac{1}{\bar{\gamma}_{\mathrm{D}}}\right)^{-k}, \end{aligned} \tag{24}$$

where $\mathrm{Ei}(\cdot)$ is the exponential integral function which is defined in [26].

Proof: Substitute $F_{\gamma_{\mathrm{e2e}}}(x)$ of (21) into (23), after some mathematical manipulations we have

$$C = \frac{1}{\ln 2}\sum_{l=0}^{N_r^{\mathrm{R}}-1}\sum_{m=0}^{N_r^{\mathrm{D}}-1} \frac{1}{l!m!\bar{\gamma}_{\mathrm{R}}^{l}\bar{\gamma}_{\mathrm{D}}^{m}} \int_0^{\infty} \frac{e^{-\frac{x}{\bar{\gamma}_{\mathrm{R}}}-\frac{x}{\bar{\gamma}_{\mathrm{D}}}}x^{l+m}}{1+x}dx. \tag{25}$$

Applying eq.(3.353.5) in [26] to solve the integral in (25), the ergodic capacity for SM-FD relay system is derived as in (24) of Theorem 3.

4. Numerical Results and Discussions

In this section, to validate the derived mathematical expressions in the previous sections, we provide analytical results together with the Monte-Carlo simulation results for comparison. Moreover, the performance of the SM-FD relay system is also investigated to understand the impact of the RSI, data transmission rate and antenna numbers on the system performance. The parameters used for evaluation are chosen as follows: the average transmit power $P_{\mathrm{S}} = P_{\mathrm{R}} = P$, the average SNR is defined as $\mathrm{SNR} = \frac{P}{\sigma^2}$, the variance of AWGN $\sigma^2 = 1$. For ease of presentation, both S and R use two transmitting antennas, i.e. $N_t = 2$, while the number of receiving antennas N_r^{R} and N_r^{D} are set to be equal and varies from 2 to 4 for evaluations. The simulation results were obtained using 10^6 channel realizations.

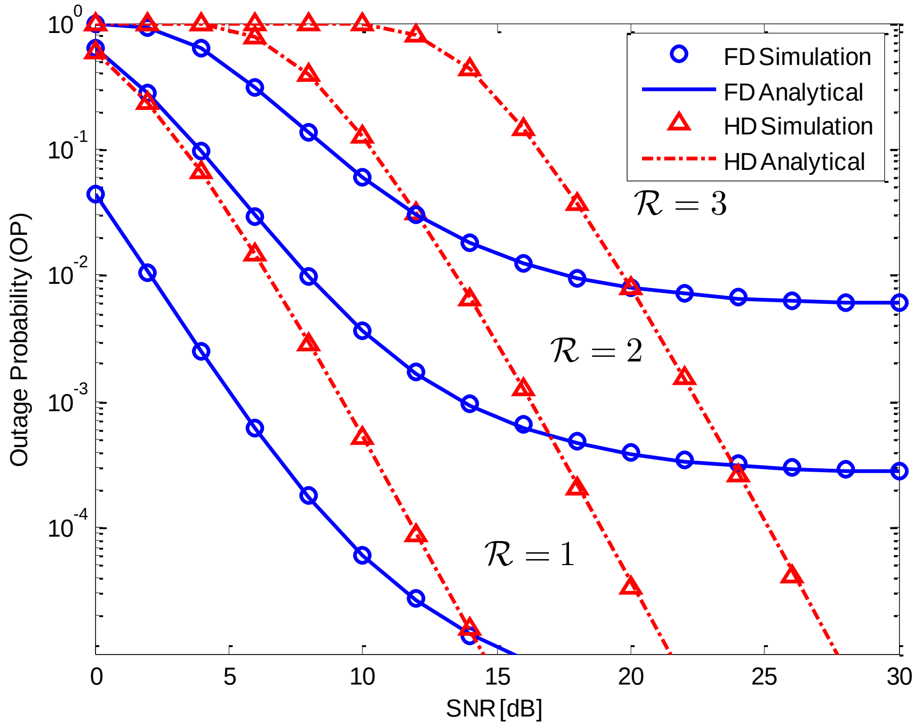

Fig. 2. The impact of data transmission rate $\mathcal{R}$ on the OP *of the SM-FD relay system, $N_r^{\mathrm{R}} = N_r^{\mathrm{D}} = 4$, $\tilde{\Omega} = -10$ dB.*

Fig. 2 illustrate the impact of the data transmission rates on the OP of the SM-FD relay network for three typical values of $\mathcal{R}$, i.e. $\mathcal{R} = 1, 2, 3$ [bit/s/Hz], and compared it with conventional SM-HD relay network. We used $N_r^{\mathrm{R}} = N_r^{\mathrm{D}} = 4$, $\tilde{\Omega} = -10$ dB. In this figure, the OPs of the SM-FD relay network are plotted by using (9) in Theorem 1. As can be seen in the figure, the analytical curves match perfectly with the simulation ones, which validates Theorem 1. Noted that the OPs of the SM-HD relay network are also used (9) after setting RSI to zero. Moreover, due to the different operation of FD and HD modes, the threshold level to determine the OP for SM-FD is always smaller than that of SM-HD relay network (specifically, the threshold for SM-FD is $x = 2^{\mathcal{R}} - 1$ while for SM-HD is $x = 2^{2\mathcal{R}} - 1$). Therefore, at the low SNR region, meaning low RSI, the OP of the SM-FD relay network is significantly smaller than SM-HD relay network. However, at high SNR regime, OPs of the SM-FD relay network suffer an outage floor due to the impact of RSI. On the other hand, it is obvious that the transmission rate has a strong impact on the OP performance of the SM-FD relay network. As shown in Fig. 2, the higher transmission rate, the lower OPs performance of the SM-FD relay system and the sooner the outage floor is reached.

Fig. 3 investigates the SEP performance of the SM-FD relay network versus the average SNR, where the BPSK modulation is used (i.e. $a = 1, b = 2$), $\tilde{\Omega} = -10$ dB with the different number of reception antennas $N_r^{\mathrm{R}} = N_r^{\mathrm{D}} = 4$. In this figure, we use

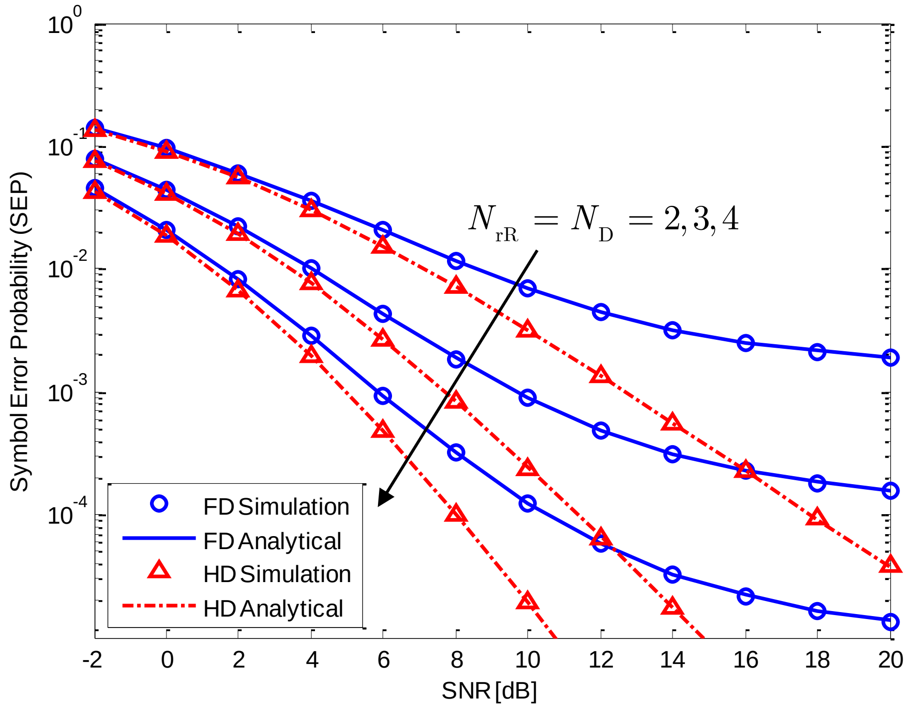

Fig. 3. The SEP*s of the SM-FD relay system for different number of reception antennas* $N_r^{\mathrm{R}} = N_r^{\mathrm{D}} = 4$, $\tilde{\Omega} = -10$ *dB.*

eq. (19) of Theorem 2 to plot the SEP curves of the SM-FD relay network. The SEPs of the SM-HD relay network are also obtained from eq. (19) by setting the RSI to zero. As shown in Fig. *3*, the SEP of SM-FD system is alway worse than that of the SM-HD due to the impact of the RSI in the FD mode. Moreover, at high SNR regime, the SEP of SM-FD system suffer an error floor. It is because the RSI is expressed as $\sigma^2_{\mathrm{RSI}} = \tilde{\Omega}P$, thus, higher transmission power results in higher RSI. For example, for $N_r = 2$, the SEP of the SM-FD relay goes to the error floor quickly at 2.10^{-3}. Besides, when increases the number of reception antennas, the SEP performance of both SM-FD and SM-HD systems is significantly improved due to the diversity gain. With 4 reception antennas, the SM-FD relay system suffer an error floor at 10^{-5} while the SM-HD relay system reaches $\mathrm{SEP} = 10^{-5}$ at $\mathrm{SNR} = 11$ dB and further decreases with increasing SNR.

In Fig. *4*, the impact of the RSI on the SEP performance of the SM-FD relay system is investigate for the BPSK modulation, $N_r = 4$ and different values of $\tilde{\Omega}$ and SNR. It is obvious that the RSI has a strong impact on the SEP of the SM-FD relay system, especially when the RSI is high. Particularly, when the RSI is very small, i.e. $\tilde{\Omega} = -20$ dB, the SEPs of the SM-FD and SM-HD system are nearly the same. When RSI is larger (by increasing SNR and/or $\tilde{\Omega}$), the SEP performance gap between FD and HD mode is higher. For example, when $\tilde{\Omega} = -10$ dB, the performance gap is about 2 times at $\mathrm{SNR} = 5$ dB, and increases to 10 times at $\mathrm{SNR} = 10$ dB. Thus, using larger

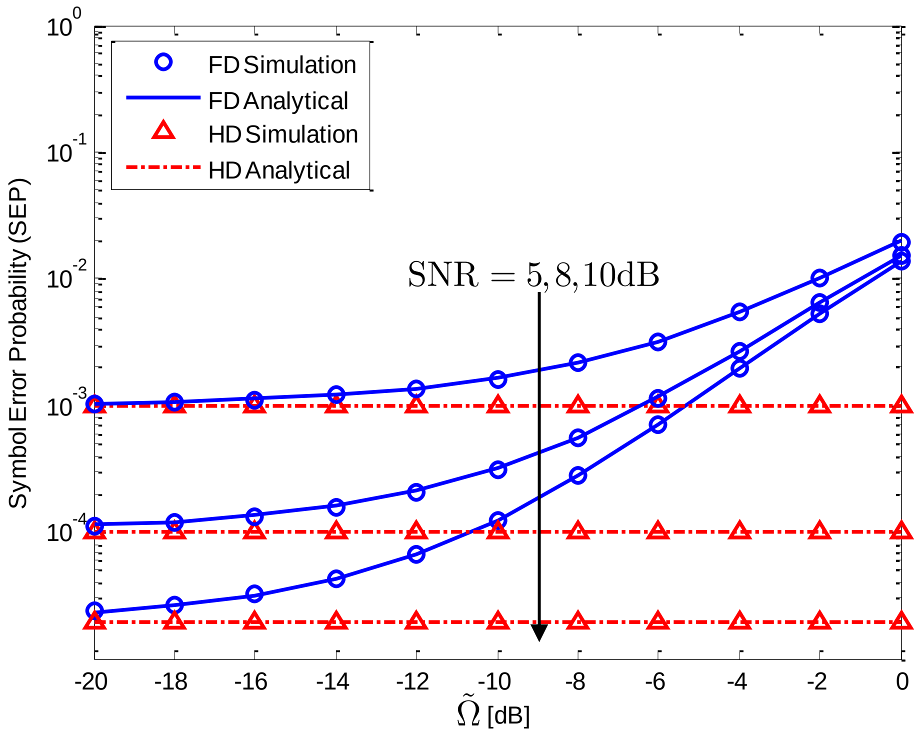

Fig. 4. Impact of the RSI on the SEP *performance of the SM-FD relay system.*

transmission power at the FD relay node is not the effective solution to improve the system performance.

Fig. *5* shows the superiority of the SM-FD relay over SM-HD relay system in terms of the ergodic capacity when the RSI level is small. In this figure, the analytical ergodic capacity curves of the SM-FD relay system are obtained by using (24) of Theorem 3, while the ergodic capacity of SM-HD relay system is determined by one-half of the capacity of the SM-FD system with the RSI level being set to zero. As shown in Fig. *4* and Fig. *5*, when the RSI is large, i.e. $\tilde{\Omega} = 0, -5$ dB, the capacity of the SM-FD relay is larger but not significant than the SM-HD relay system at low SNR region while the SEP performance is much lower than the SM-HD relay system. When the RSI is smaller with $\tilde{\Omega} = -10, -20$ dB, the SM-FD relay system is nearly double the capacity compared with SM-HD relay system in the observed region with an acceptable performance degradation. Thus, depending on the system requirements we can choose the FD or HD mode for the relay node.

5. Conclusion

SM-FD technique is a promising transmission solution for MIMO wireless communications in both context of point-to-point and relaying transmission systems. In this paper,

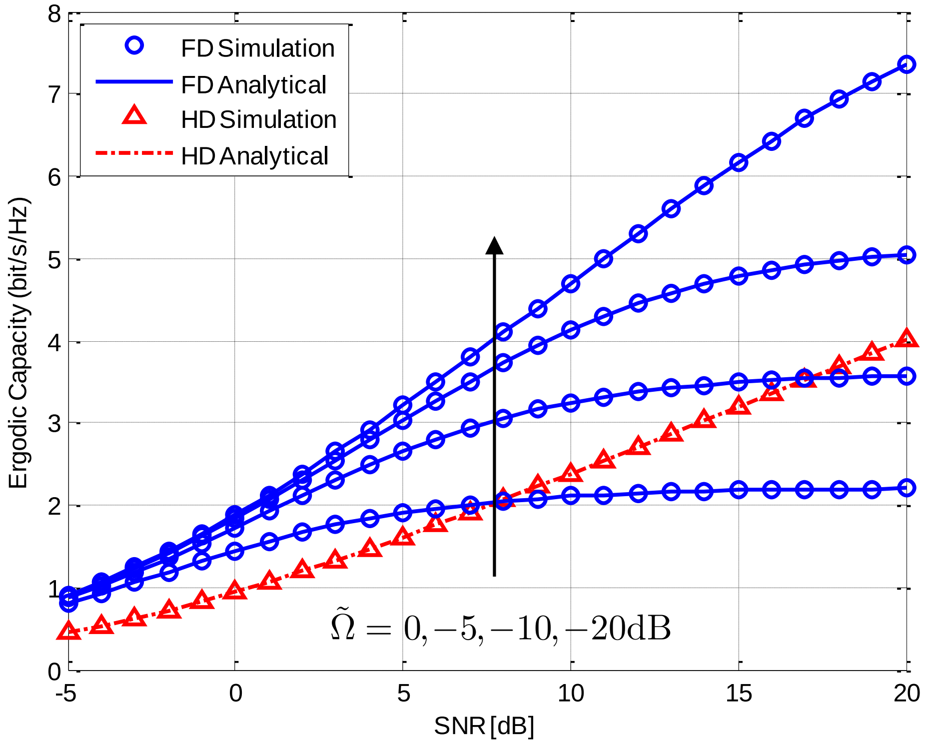

Fig. 5. Ergodic capacity comparison of the SM-FD and SM-HD relay system, $N_r^{\mathrm{R}} = N_r^{\mathrm{D}} = 4$.

we introduce a mathematical framework to derive the exact closed-form expressions for the OP, SEP and ergodic capacity of the SM-FD relay system in the presence of SI channels, and compare with that of SM-HD relay system. Both numerical and simulation results showed that the RSI, data transmission rate and number of received antennas have a substantial impact on the system performance. This result can be used as a reference to choose the FD/HD mode for the relay node depending on requirements of specific system.

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Manuscript received 30-7-2019; Accepted 18-12-2019.

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PHÂN TÍCH PHẨM CHẤT MẠNG GIẢI MÃ VÀ CHUYỂN TIẾP SONG CÔNG TRÊN CÙNG BĂNG TẦN SỬ DỤNG KỸ THUẬT ĐIỀU CHẾ KHÔNG GIAN

Tóm tắt

Bài báo này đánh giá phẩm chất và dung lượng mạng chuyển tiếp song công trên cùng băng tần (IBFD: In-Band Full-Duplex) sử dụng kỹ thuật điều chế không gian (SM: Spatial Modulation) trong trường hợp triệt nhiễu tự giao thoa (SIC: Self-Interference Cancellation) không hoàn hảo. Bằng phương pháp giải tích, chúng tôi tìm ra biểu thức chính xác về xác suất dừng (OP: Outage Probability), xác suất lỗi ký hiệu (SEP: Symbol Error Probability) và dung lượng trung bình (Ergodic capacity) của mạng chuyển tiếp SM-FD qua kênh pha-đinh Rayleigh. Từ đó đánh giá được ảnh hưởng của nhiễu dư (RSI: Residual Self-Interference), số lượng ăng-ten thu và tốc độ truyền dẫn đến phẩm chất và dung lượng hệ thống khi so sánh với mạng chuyển tiếp SM bán song công (HD: Half-Duplex). Cuối cùng, mô phỏng Monte-Carlo được sử dụng để kiểm chứng kết quả phân tích.