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On the Performance of Full-duplex Two-way Relay Channels with Spatial Modulation

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Abstract—In this paper, the spatial modulation (SM) technique is employed at the source and relay nodes in a full-duplex two-way relay channel (FD-TWRC) to support spectral-efficient bidirectional communications while guaranteeing a low cost implementation. Maximum likelihood (ML) detectors are employed at each node that is subject to an intrinsic self-loop interference (SI). We first propose a tight upper bound on the average bit error probability (ABEP). Then based on the ABEP upper bound, an asymptotic ABEP expression is derived in the high SNR regime. Exploiting the asymptotic ABEP, an exact SNR threshold for the selection between FD-TWRC-SM and half-duplex (HD)-TWRC-SM is derived in a closed form, which sheds light on when it is beneficial to select the FD (or HD) mode. In addition, the power allocation (PA) among sources and relay is investigated, through which an optimal PA factor in terms of ABEP is obtained. All analytical results derived in this paper are verified by Monte Carlo simulations, from which some new insights are obtained on the performance of FD-TWRC-SM.

Index Terms—Two-way relay channel, full-duplex relay, spatial modulation, self-loop interference.

I. INTRODUCTION

Multi-antenna techniques are widely accepted as a key enabler in achieving a high data rate and spectral efficiency in the next generation of communications. However, a significant amount of power is consumed for transmitting signal [1], especially when multiple transmit antenna elements work simultaneously due to the same number of transmit radio frequency (RF) chains. Driven by this, the spatial modulation (SM) technique has been proposed to reduce the cost of the multi-antenna systems [2]–[6]. The performance of SM systems with multiple antennas has been evaluated through analytical analysis [7]–[12] and measurement [13]–[16].

The SM technique has been applied to various relay systems [17]–[27]. A relay system employing SM, which utilizes the relay-selection information to achieve a higher throughput is proposed in [17]. In [18], the performance of the dual-hop space shift keying (SSK) system is evaluated. A dual-hop SM system is proposed and analyzed in [19]. A two-hop space-time shift keying (STSK) relay system is introduced and its performance is analyzed in [20]. In [21], the authors analyzed the distributed SSK in relay-aided cellular networks. Furthermore, the authors in [22] analyzed the performance of SSK relay systems with multiple cooperative relays considering both amplify-and-forward (AF) and decode-and-forward (DF) protocols. A bit error probability analysis of SSK in DF relay channels with best relay selection is conducted in [23]. In [24], the authors proposed a distributed SM system for multi-relay networks whose diversity was analyzed analytically. In addition, the authors in [25] proposed a differential SM for dual-hop AF relaying system. A framework to analyze the average bit error probability (ABEP) of the SM system with a single-antenna AF node was proposed in [26]. The authors in [27] proposed an SM based cooperative diversity protocol where the network nodes act as relays to help forward the source data, while transmitting their own data.

However, all these existing work above considered only half-duplex (HD) relays, which have to transmit and receive signals in orthogonal channels. Driven by the inherent spectrum inefficiency suffered by HD relay systems, there has been an increasing interest in full-duplex (FD) relays that are capable of transmitting and receiving signals in the same frequency band simultaneously, e.g., [28] and the references therein. Although a substantially higher spectrum efficiency can be promised by the FD relay system, the self-loop interference (SI) that leaks between the transmit and receive antennas of the FD relay node needs to be carefully addressed [29]. Inspired by the benefits of FD transmissions, some recent work has investigated FD-SM transmission in non cooperative relay systems, e.g., [30]–[32].

The impact of SI on the two-way relay channel (TWRC) with a FD relay, which is a spectral-efficient transmission protocol for wireless networks, has been investigated in [33]–[38]. It is shown that when SI is weak enough, the TWRC with the FD relay achieves a higher spectral efficiency than the TWRC with the HD relay. On the other hand, the performance of the HD-TWRC with SM has been investigated in [39]–[41]. Motivated by the promising performance of the TWRC...
and FD relaying, in this paper we consider a FD TWRC with SM performed at each node to support the bi-directional communications between two end users, which is referred to as FD-TWRC-SM as illustrated in Fig. 1. The main contributions of this paper are summarized as follows:

1) A FD-TWRC-SM system is proposed and investigated to enhance the system spectral efficiency. To the best of our knowledge, this is the first attempt to apply SM techniques to the TWRC with FD relaying in the literature.

2) Taking into account the impact of the residual SI, an analytical pairwise error probability (PEP) and a tight upper bound on the ABEP of the FD-TWRC-SM are respectively obtained in closed forms. On this basis, we find that the diversity order of FD-TWRC-SM significantly depends on the quality of the SI cancellation.

3) Comparisons between HD-TWRC-SM and FD-TWRC-SM schemes are conducted to provide insights into the selection between FD and HD modes. Under a given strength of SI cancellation, an exact signal-to-noise ratio (SNR) threshold, below which the FD-TWRC-SM outperforms the HD-TWRC-SM in terms of the ABEP, is analytically derived.

4) A power allocation (PA) scheme is applied that allocates different transmit powers to all nodes subject to a sum power constraint. The optimal PA factor that leads to the best ABEP is derived in a closed form.

5) All analytical results are verified through numerical results and employed to analyze the system performance of FD-TWRC-SM under various conditions. Some useful insights are obtained regarding the performance of FD-TWRC-SM.

The remainder of this paper is organized as follows. In Section II, the system model of FD-TWRC-SM is introduced. In Section III, an analytical union upper bound on the ABEP is obtained. Then in Section IV, the proposed ABEP upper bound is employed to evaluate the system performance of FD-TWRC-SM. Simulation results are provided in Section V to demonstrate the effectiveness of the proposed FD-TWRC-SM. Finally, Section VI concludes this paper.

II. SYSTEM MODEL OF FD-TWRC-SM

We consider a FD-TWRC-SM with DF relaying protocol at the relay node that is similar to the TWRC with the FD relaying in [38]. As shown in Fig. 1, the system consists of two source nodes denoted by $S_1$, $i = 1, 2$, and one FD relay node denoted by $R$, where $S_1$ and $S_2$ want to exchange information with the help of $R$. There is no direct link between the two sources due to a very large distance between them [42]. All $S_1$, $S_2$, and $R$ transmit signals using the SM scheme. In an SM transmission, $S_1$ and $S_2$ are respectively equipped with $N_1$ and $N_2$ transmit antennas and only a single transmit antenna in the transmit antenna array of each node is activated. The index of the activated transmit antenna is employed to carry a block of bits to increase the overall spectral efficiency. On the other hand, $N_{R,1}$, $N_{R,2}$, and $N_{R,r}$ receive antennas are respectively equipped at $S_1$, $S_2$, and $R$ to perform the maximum likelihood (ML) detection. A detailed design of SM transceivers can be found in [2].

Without loss of generality, we consider a wireless fading channel that remains static within a period of a time block of symbols but changes independently from one time block to another [34], [43]–[47]. $h_{ir}[k, n_i]$ denotes the channel amplitudes from the $n_i$th transmit antenna of $S_i$ to all receive antennas at $R$ in the $k$th time block and $h_{rr}[k, n_r]$ denotes the channel amplitudes from the $n_r$th transmit antenna of $R$ to all receive antennas at $S_i$ in the $k$th time block. Both source nodes and the relay node are full duplex and suffer from SI. All channel amplitudes follow independent and identically distributed (i.i.d.) Rayleigh distributions. The transmit SNRs
The transmission of each block of information $I_i \triangleq (m_i, n_i)$ is carried out in two time blocks. In the first time block, both $S_i$ transmit $I_i = (m_i, n_i)$ to $R$, and $R$ detects the information as $\hat{I}_i = (\hat{m}_i, \hat{n}_i)$. In the second time block, $R$ transmits $\hat{I}_i = (\hat{m}_i, \hat{n}_i)$ to both $S_i$, and $S_i$ detect the information as $\hat{I}_i \triangleq (\hat{m}_i, \hat{n}_i)$. From the visual angle of $I_i$ transmitted at the $k$th time block, interference in both time blocks are shown in Fig. 2. In the $k$th time block, $S_i$ transmit the $m_i$th $M_r$-quadrature-amplitude modulation (QAM) symbol through the $n_i$th transmit antenna simultaneously to $R$ using the SM transmission scheme. The relay $R$, with one-block processing delay, broadcasts the received information blocks in the previous time block $k-1$, which is denoted as $(\hat{m}_i', \hat{n}_i')$, to the sources simultaneously, thus causing a SI.

The received signal $y_r[k]$, consisting of the received signal at each receive antenna at $R$ in the $k$th time block, is composed of the signal $x_1[m_1]$ that is transmitted over channel from $S_1$ to $R$, the signal $x_2[m_2]$ that is transmitted over channel from $S_2$ to $R$, the SI $\sqrt{\rho_r^{-1}}h_{rr}[k, \hat{n}_i']x_r[\hat{m}_i']$, and noise $w_r[k] \sim \mathcal{CN}(0, \sigma_r^2)$ as (1).

In this paper, we consider SM schemes with QAM signal constellations at each node. The signal constellation of the phase-shift-keying (PSK) SM can be readily obtained following the same steps of the QAM SM and is thus omitted here. Without loss of generality, we assume that $S_i$ has $N_i$ transmit antennas and an $M_i$-QAM signal constellation diagram. $R$ has $N_r$ transmit antennas and an $M_r$-QAM signal constellation diagram. Benefited from the SM scheme, even though a large scale antenna array is equiped at the relay node, we need only one transmit RF chain and therefore the power consumption and the receive complexity of the system is acceptable. For tractable analysis, we restrict that $M_i = M_1 M_2$ and $N_r = N_1 N_2$, and assume that the signals transmitted by both sources in the first hop are Gray coded. In the $k + 1$th time block, at the relay node, the information from both source nodes are estimated, i.e., $\hat{n}_1, \hat{n}_2, \hat{m}_1, \hat{m}_2$. Then the relay node activates the $\hat{n}_i = \hat{n}_i + (\hat{n}_i - 1)N_1$th antenna to transmit the signal $x_r[\hat{m}_i] = x_r[\hat{m}_1 + (\hat{m}_2 - 1)M_1]$ that corresponds to the $\hat{m}_1$th row and the $\hat{m}_2$th column of the $M_i$-QAM signal constellation diagram. That is, the estimated symbols $\hat{m}_1$ and $\hat{m}_2$ are interpreted as the Quadrature and In-phase components respectively, which are then used to locate the transmitted symbol by the relay. Simultaneously, the sources transmit $(\hat{m}_1', \hat{n}_1')$ to the relay $R$ and cause a SI. Thus, the received signal at $S_i$ in the subsequent time block $k + 1$ is given as (2), where $w_i[k] \sim \mathcal{CN}(0, \sigma_i^2)$. Without loss of generality, we assume that $\sigma_r^2 = \sigma_i^2 = \sigma^2$. The optimal detector based on the ML principle is deployed at each node. We assume that the exact instantaneous channel state information (CSI) and perfect time synchronization are available at the receiver side, as in [2], [7], [8]. According to (1), we have (3), and the principle of the ML receiver is to find out $(\hat{n}_1, \hat{n}_2, \hat{m}_1, \hat{m}_2)$ to maximize the likelihood function, i.e., (4).

Assuming that the sources are equipped with buffers, each

$$y_r[k] = \sqrt{\rho_1}h_{1r}[k, n_1]x_1[m_1] + \sqrt{\rho_2}h_{2r}[k, n_2]x_2[m_2] + \sqrt{\rho_r^{-1}}h_{rr}[k, \hat{n}_i']x_r[\hat{m}_i'] + w_r[k]$$  

Received from $S_1$  
Received from $S_2$  
Loop Interference  
Noise  

Fig. 2. Intended signal and interference signal for the information transmitted in the $k$th time slot.
source is aware of its own transmitted message in the previous time block. Specifically, since \((n_2, m_2)\) was transmitted by \(S_2\) and stored in the buffer at \(S_2\), a simple self-interference cancellation can be performed by \(S_2\) to eliminate the uncertainty of \((n_2, m_2)\). Then the set of candidate \((\hat{n}_r, \hat{m}_r)\) can be narrowed to \((\hat{n}_1 + (n_2 - 1)N_1, \hat{m}_1 + (m_2 - 1)M_1)\). Thus, the detection process at \(S_2\) is given by (6). A similar detection process is applied to \(S_1\).

Note that the original symbols denote the actual message that is transmitted. Symbols with \(\hat{\cdot}\) denote the messages estimated by the detector at \(R\), whereas symbols with \(\hat{\cdot}\) denote the messages estimated by the detector at the sources. These notations are also applied to the antenna indices \(n_i\) and signal indices \(m_i\).

### III. ABEP Upper Bound

In this section, we analyze the error performance of the TWRC-SM analytically. For arbitrary MIMO systems, the analysis of the exact ABEP is almost intractable due to the complex multidimensional integrals. Instead, the union upper bound technique is widely used to calculate the ABEP upper bound based on PEP \([7, \text{Eq. (3)}]\), \([8, \text{Eq. (5)}]\). If the analytical PEP can be obtained, an upper bound on the ABEP of the information transmission from \(S_1\) to \(S_2\) via \(R\) is given by (7), where \(I_1\) denotes the transmitted message from \(S_1\). \(PEP(m_1, n_1; \hat{n}_1, \hat{m}_1)\) denotes the probability of choosing the wrong symbol \(\hat{I}_1\) assuming that there are only two symbols \(I_1\) and \(\hat{I}_1\) possibly being transmitted. \(D_H(\hat{n}_1, \hat{m}_1, n_1, m_1)\) denotes the Hamming distance between \(\hat{I}_1\) and \(I_1\).

Moreover, the pairwise error \(I_1 \rightarrow \hat{I}_1\) may occur under any possible \(I_1\) that is detected by \(R\). Therefore, according to the total probability theorem, we have

\[
y_i[k + 1] = \sqrt{p_r} h_{r_i}[k + 1, \hat{n}_r] x_r[\hat{m}_r] + \sqrt{p_i} h_{i_i}[k + 1, n'_i] x_i[m'_i] + w_i[k + 1]
\]

\[
y_r[k] \sim CN(\sqrt{p_r} h_{r_i}[k, n_1] x_r[\hat{m}_r], \sqrt{p_r} h_{r_i}[k, n_1] x_r[\hat{m}_r]) + \sqrt{p_2} h_{2_i}[k, n_2] x_2[\hat{m}_2] + \sqrt{\rho_1^{-1}} h_{1_i}[k, n'_i] x_i[m'_i] + w_r[k + 1]
\]

\[
(\hat{n}_1, \hat{m}_1, \hat{m}_2) = \arg \max_{n_1, \hat{m}_1, m_1} \left\{ e^{[\rho_1^{-1} |x_r[\hat{m}_r]|^2 + 1]} \right\}
\]

\[
(\hat{n}_2, \hat{m}_2) = \arg \min_{\hat{m}_2} \{ |y_r - \sqrt{p_r} h_{r_i}[k, \hat{n}_1] x_r[\hat{m}_r] - \sqrt{p_2} h_{2_i}[k, \hat{n}_2] x_2[\hat{m}_2]|^2 \}
\]

\[
\hat{m}_1 = \arg \min_{\hat{m}_1} \{ |y_2 - \sqrt{p_r} h_{r_i}[k + 1, \hat{n}_1 + (n_2 - 1)N_1] x_r[k + 1 + \hat{m}_1 + (m_2 - 1)M_1]| \}
\]

\[
\sum_{I_1=(1,1)}^{(M_1,N_1)} \sum_{I_2=(1,1)}^{(M_2,N_2)} \sum_{I_3=(1,1)}^{(M_1,N_1)} \sum_{I_4=(1,1)}^{(M_2,N_2)} D_H(\hat{n}_1, \hat{m}_1, n_1, m_1) \ PEP(m_1, n_1; \hat{m}_1, \hat{n}_1; m_2, n_2)
\]

\[
\text{ABEP} \leq \frac{N_1 N_2 M_1 M_2 \log_2(N_1 M_1)}{\sum_{I_1=(1,1)}^{(M_1,N_1)} \sum_{I_2=(1,1)}^{(M_2,N_2)} \sum_{I_3=(1,1)}^{(M_1,N_1)} \sum_{I_4=(1,1)}^{(M_2,N_2)} D_H(\hat{n}_1, \hat{m}_1, n_1, m_1) \ PEP(m_1, n_1; \hat{m}_1, \hat{n}_1; m_2, n_2) - \sum_{I_1=(1,1)}^{(M_1,N_1)} \sum_{I_2=(1,1)}^{(M_2,N_2)} \ PEP(m_1, n_1; \hat{m}_1, \hat{n}_1; m_2, n_2)}
\]

\[
\text{ABEP} \leq \frac{N_1 N_2 M_1 M_2 \log_2(N_1 M_1)}{\sum_{I_1=(1,1)}^{(M_1,N_1)} \sum_{I_2=(1,1)}^{(M_2,N_2)} \sum_{I_3=(1,1)}^{(M_1,N_1)} \sum_{I_4=(1,1)}^{(M_2,N_2)} D_H(\hat{n}_1, \hat{m}_1, n_1, m_1) \ PEP(m_1, n_1; \hat{m}_1, \hat{n}_1; m_2, n_2)}
\]

Proof: See Appendix A.

Proposition 1 provides a framework to derive the analytical upper bound on the ABEP of TWRC-SM systems by giving

\[
\text{ABEP} \leq \frac{N_1 N_2 M_1 M_2 \log_2(N_1 M_1)}{\sum_{I_1=(1,1)}^{(M_1,N_1)} \sum_{I_2=(1,1)}^{(M_2,N_2)} \sum_{I_3=(1,1)}^{(M_1,N_1)} \sum_{I_4=(1,1)}^{(M_2,N_2)} D_H(\hat{n}_1, \hat{m}_1, n_1, m_1) \ PEP(m_1, n_1; \hat{m}_1, \hat{n}_1; m_2, n_2)}
\]
where $\sqrt{\xi}$ is defined as (17).

Proof: Since the residual SI and the noise are both complex Gaussian distributed with variances of $\xi_1$ respectively, the transmission from $R$ to $S$ has $P_{EP,2}$ in closed forms. For the FD-TWRC-SM systems, $P_{EP,1r}$ and $P_{EP,2r}$ are derived in Lemma 1 and Lemma 2, respectively. For the HD-TWRC-SM systems, $P_{EP,1r}$ and $P_{EP,2r}$ are derived in Lemma 3.

**Lemma 1.** The PEP of the first hop transmission from $S_1$ and $S_2$ to $R$ in an FD-TWRC-SM system is computed as follows:

$$P_{EP,1r} = \frac{M_1 M_2}{N_R} \sum_{m_1=1}^{M_1} \sum_{m_2=1}^{M_2} R(N_R - v)$$

where $v$ is computed by (15), $R(\kappa, N_R) \triangleq \left\lfloor \frac{1}{2} (1 - \sqrt{\kappa}) \right\rfloor^{|N_R|} \sum_{q=0}^{N_R-1} C_k^q \left(\frac{1}{2} (1 + \sqrt{\kappa}) \right)^q$, and $C_k^q$ denotes the binomial coefficient indexed by $n$ and $k$.

Proof: See Appendix B.

**Lemma 2.** The PEP of the second hop transmission from $R$ to $S_2$ in an FD-TWRC-SM system is computed as follows:

$$P_{EP,2r} = \frac{M_2}{M_1} \sum_{m_2=1}^{M_2} R(N_R - \xi)$$

where $\xi$ is defined as (17).

Proof: Since the residual SI and the noise are both complex Gaussian distributed with variances of $\rho_2^{1-\mu}$ and 1, respectively, the transmission from $R$ to $S_2$ is equivalent to the SM transmission with an average SNR of $\rho_2 r_2 = \rho_2^{1-\mu} |x_2|^2$. Similar to the derivations in Appendix B, we have $P_{EP,2r} = Q(\sqrt{d_{12}}, r_{12})$, where $d_{12}$ is defined as (18), and $Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^\infty e^{-t^2/2} dt$ is the tail probability of the standard normal distribution.

**Lemma 3.** For HD-TWRC-SM systems, $P_{EP,1r}$ and $P_{EP,2r}$ are respectively derived as

$$P_{EP,1r} = R(N_R - v_{HD})$$

$$P_{EP,2r} = R(N_R - \xi_{HD})$$

where $v_{HD}$ and $\xi_{HD}$ are respectively given in Eqs. (21) and (22).

Proof: Since there is no SI in the HD-TWRC-SM, by substituting $x_r[m_2'] = x_2[m_2'] = 0$ into (15) and (17) respectively, we obtain (19) and (20) by simple algebraic manipulations based on (14) and (16).

**IV. PERFORMANCE ANALYSIS**

In this section, we analyze the system performance of the TWRC-SM systems over i.i.d. Rayleigh fading channels. Especially, we will first obtain asymptotically tight performance bounds that provide insights on the fundamental properties of FD-TWRC-SM systems. And then we will develop an optimal FD and HD switching scheme in TWRC-SM systems. To this, a corresponding decision threshold will be given as the root of a polynomial equation.

**A. Asymptotic ABEP and diversity order**

We first derive an asymptotic ABEP of the FD-TWRC-SM transmission from $S_1$ to $S_2$ in the following Proposition 2.

Due to space limitations, we omit the detailed derivation.
Proposition 2. Assuming $\rho_r = \rho_t = \rho$, an asymptotic ABEP of FD-TWRC-SM is computed by (23), where $G_1$ and $G_2$ are respectively weighted by Eqs. (24) and (25) with (26) and (27), $N_{R_2} = \min\{N_{R,r}, N_{R,2}\}$, $\left( k_1, k_2, \ldots, k_m \right) \triangleq \left( k_1^{\ell_1}, k_2^{\ell_2}, \ldots, k_m^{\ell_m} \right)$, and

$$K_1(q) = \sum_{\ell_1=1}^{M_{1}}} \left( 2N_{R,2} - 1 \right) |x_r| |\hat{n}_{r_{1}}|^2 q, \quad (28)$$

$$K_2(q) = \sum_{\ell_2=1}^{M_{2}}} \left( 2N_{R,2} - 1 \right) |x_2| |\hat{m}_{2}|^2 q, \quad (29)$$

Proof: See Appendix C.

Remark 1. It is observed in (23) that the ABEP increases dramatically with the decreasing SI cancellation factor $\mu$. From (23), we find that the ABEP is a weighted summation of $\rho^{-N_{R,r}r + q(1 - \mu)}$, $\rho^{-N_{R,r}q(1 - \mu)}$, and $\rho^{-N_{R,2}r + q(1 - \mu)}$ respectively when $N_{R,r} < N_{R,2}$, $N_{R,2} = N_{R,r}$, and $N_{R,2} > N_{R,r}$. In the high SNR regime, the worst term dominates the slope of the ABEP, which is defined as the diversity order [7, Proposition 4]. Thus, when $N_{R,r} < N_{R,2}$, the diversity order is $\min\{N_{R,2} - q(1 - \mu)\} = \mu N_{R,r}$. Similarly, when $N_{R,r} = N_{R,2}$ and $N_{R,r} > N_{R,2}$, we have diversity orders $\mu N_{R}$ and $\mu N_{R,r}$, respectively. Therefore, the diversity order of the FD-TWRC-SM system is $\min\{\mu N_{R,r}, \mu N_{R,2}\}$. We take $N_{R,r} = 1$ and $N_{R,2} = 2$ as an example, from the first line of (23), we obtain $ABEP_{FD,A} = G_1[K_1(0)\rho^{-1} + K_2(1)\rho^{-\mu}] \triangleq G_1 K_1(1)\rho^{-\mu}$ and thus the diversity order is $\mu$.

However, if we use $\lim_{\rho \to +\infty} \sum_{q=0}^{N_{R}} K(q)\rho^{-N_{R}q(1 - \mu)} = G\left(K(q)\rho^{-N_{R}}\mu \right)$ [7, Corollary 5] in (23) by letting $q = N_{R}$, then the obtained asymptotic ABEP will not be tight enough to analyze the system performance because when $\mu$ is large, $\rho^{-N_{R}(1 - \mu)} = \rho^{-\mu}N_{R} << \rho^{-\mu}N_{R}$ may not hold. Thus, we use (23).

\[
\begin{align*}
\nu_{HD} &= \left\{ \begin{array}{ll}
\frac{1}{4} \rho |x_1[1]| - x_1[1]|^2 + \rho_2 |x_2[2]| - x_2[2]|^2, & \hat{n}_1 = n_1, \hat{n}_2 = n_2 \\
\frac{1}{4} \rho |x_1[1]| - x_1[1]|^2 + \rho_2 (|x_2[2]|^2 + |x_2[2]|^2), & \hat{n}_1 = n_1, \hat{n}_2 \neq n_2 \\
\frac{1}{4} \rho (|x_1[1]|^2 + |x_1[1]|^2) + \rho_2 (|x_2[2]|^2 - |x_2[2]|^2), & \hat{n}_1 \neq n_1, \hat{n}_2 = n_2 \\
\rho_2 |x_1[1]| - x_1[1]|^2 + \rho_2 (|x_2[2]|^2 + |x_2[2]|^2), & \hat{n}_1 \neq n_1, \hat{n}_2 \neq n_2 \\
\rho_2 (|x_1[1]|^2 + |x_1[1]|^2) + \rho_2 (|x_2[2]|^2 + |x_2[2]|^2), & \hat{n}_1 \neq n_1, \hat{n}_2 \neq n_2 \\
\end{array} \right.
\end{align*}
\]

\[
\xi_{HD} = \left\{ \begin{array}{ll}
G_1 \sum_{q=0}^{N_{R}} K_1(q)\rho^{-N_{R}r + q(1 - \mu)}, & N_{R,r} < N_{R,2} \\
G_2 \sum_{q=0}^{N_{R,2}} K_2(q)\rho^{-N_{R,2}r + q(1 - \mu)}, & N_{R,r} > N_{R,2} \\
\end{array} \right.
\]

\[
G_1 = \frac{1}{M_1 M_2} \sum_{m_1=1}^{M_1} \sum_{\ell_1=1}^{M_2} \left\{ \begin{array}{ll}
\left( \frac{M_1 M_2}{2} \right) K_1(q) \rho^{-N_{R}r + q(1 - \mu)} = 0 \\
\end{array} \right.
\]

\[
G_2 = \frac{1}{M_1 M_2} \sum_{m_1=1}^{M_1} \sum_{\ell_1=1}^{M_2} \left[ \begin{array}{ll}
\frac{\rho |x_1[1]| - x_1[1]|^2 + \rho_2 |x_2[2]| - x_2[2]|^2, & \hat{n}_1 = n_1, \hat{n}_2 = n_2 \\
\frac{\rho |x_1[1]| - x_1[1]|^2 + \rho_2 (|x_2[2]|^2 + |x_2[2]|^2), & \hat{n}_1 = n_1, \hat{n}_2 \neq n_2 \\
\frac{\rho (|x_1[1]|^2 + |x_1[1]|^2) + \rho_2 (|x_2[2]|^2 - |x_2[2]|^2), & \hat{n}_1 \neq n_1, \hat{n}_2 = n_2 \\
\frac{\rho_2 |x_1[1]| - x_1[1]|^2 + \rho_2 (|x_2[2]|^2 + |x_2[2]|^2), & \hat{n}_1 \neq n_1, \hat{n}_2 \neq n_2 \\
\frac{\rho_2 (|x_1[1]|^2 + |x_1[1]|^2) + \rho_2 (|x_2[2]|^2 + |x_2[2]|^2), & \hat{n}_1 \neq n_1, \hat{n}_2 \neq n_2 \\
\end{array} \right.
\]

\[
\xi_0 = \left\{ \begin{array}{ll}
|x_1[m_1] - x_1[m_1]|^2 + |x_2[m_2] - x_2[m_2]|^2, & \hat{n}_1 = n_1, \hat{n}_2 = n_2 \\
|x_1[m_1] - x_1[m_1]|^2 + |x_2[m_2]|^2 + |x_2[m_2]|^2, & \hat{n}_1 = n_1, \hat{n}_2 \neq n_2 \\
|x_1[m_1]|^2 + |x_1|m_1|^2 + |x_2[m_2]|^2 + |x_2[m_2]|^2, & \hat{n}_1 \neq n_1, \hat{n}_2 = n_2 \\
|x_1[m_1]|^2 + |x_1[m_1]|^2 + |x_2[m_2]|^2 + |x_2[m_2]|^2, & \hat{n}_1 \neq n_1, \hat{n}_2 \neq n_2 \\
\end{array} \right.
\]

\[
\xi_0 = \left\{ \begin{array}{ll}
|x_r[m_1 + (m_2 - 1)M_1] - x_r[m_1 + (m_2 - 1)M_1]|^2, & \hat{n}_r = n_r \\
|x_r[m_1 + (m_2 - 1)M_1]|^2 + |x_r[m_1 + (m_2 - 1)M_1]|^2, & \hat{n}_r \neq n_r \\
\end{array} \right.
\]
as the asymptotic performance in the high SNR regime. A verification of this remark is shown in Fig. 3, where we use $N_1 = N_2 = 4$, $M_1 = M_2 = 4$, and $N_{R,r} = N_{R,2} = 2$.

**B. Optimal selection between HD and FD modes**

In this subsection, we give comparisons of FD-TWRC-SM with its HD counterpart. To this, we first give an asymptotic ABEP of HD-TWRC-SM, which is derived based on $P_{EH}^{|HD|,1}$ and $P_{EH}^{|HD|,2}$. Following the same steps as in Appendix C, using (10) and Lemma 3, we obtain an asymptotic ABEP of HD-TWRC-SM in Lemma 4.

**Lemma 4.** Assuming an equal average SNR at the nodes, i.e., $\rho_r = \rho_i = \rho$ at the nodes, the optimal selection of either FD or HD transmission modes is determined by

$$\rho \begin{bmatrix} \frac{1}{2} \left( 1 + \right. \right. \xi (1 - \mu) \left. \rho_{O_L}^{a H} \right) \end{bmatrix}^{\min(N_{R,r}, N_{R,2})} \leq \rho \begin{bmatrix} \frac{1}{2} \left( 1 + \right. \right. \xi (1 - \mu) \left. \rho_{O_L}^{a H} \right) \end{bmatrix}^{\min(N_{R,r}, N_{R,2})}, \tag{31}$$

where $z$ is the positive real root of Eq. (32) and can be represented in a closed form when $\min(N_{R,r}, N_{R,2}) \leq 5$. If $\min(N_{R,r}, N_{R,2}) > 5$, the positive real root of Eq. (32) can be obtained by Newton-Raphson method [61].

**Remark 2.** Under the same data rate, the signal constellation order $M_i$ of HD-TWRC-SM is higher than that of FD-TWRC-SM. Therefore, it is predictable that with perfect SI cancellation, although these two systems have the same diversity order $\min(N_{R,r}, N_{R,2})$, the Euclidean distance between the symbols in HD-TWRC-SM is smaller than that in FD-TWRC-SM. Thus, FD-TWRC-SM always performs better than HD-TWRC-SM in terms of ABEP. On the other hand, in the presence of non-perfect SI cancellation, the diversity order of FD-TWRC-SM is smaller than that of HD-TWRC-SM. Thus, HD-TWRC-SM tends to perform better than FD-TWRC as the SNR increases. Thus, an interesting and challenging problem is to figure out the SNR threshold for the selection of either HD or FD mode, through which ABEPs can be minimized over the entire SNR regime. The main result is summarized in Proposition 3.

**Proposition 3.** Assuming an equal average SNR $\rho_r = \rho_i = \rho$ at the nodes, the optimal selection of either FD or HD transmission modes is determined by

$$\begin{cases} \rho \geq \frac{1}{2} \left( 1 + \right. \right. \xi (1 - \mu) \left. \rho_{O_L}^{a H} \right) \end{bmatrix}^{\min(N_{R,r}, N_{R,2})}, \tag{31} \end{cases}$$

where $z$ is the positive real root of Eq. (32) and can be represented in a closed form when $\min(N_{R,r}, N_{R,2}) \leq 5$. If $\min(N_{R,r}, N_{R,2}) > 5$, the positive real root of Eq. (32) can be obtained by Newton-Raphson method [61].

Proof: Letting $\rho_1 = \rho_2$, (35) can be rewritten as (32). Then $\rho$, which is the root of (35), can be obtained by (31).

**C. Power allocation**

In subsections IV-A and IV-B, we assumed an equal average SNR at the nodes. The PA may be applied to achieve a better ABEP performance, where $S_i$ and $R$ employ different sets of powers $\rho_i \sigma^2$ and $\rho_r \sigma^2$, accordingly. In this subsection, we aim to propose an optimal PA under a total transmit power constraint $\rho_{ALL} \sigma^2$, i.e., $2\rho_i \sigma^2 + \rho_r \sigma^2 \leq \rho_{ALL} \sigma^2$. Defining PA factor $F \triangleq \frac{\rho_i}{\rho_r}$, we have $\rho_i \leq \frac{\rho_{ALL}}{2+F}$ and $\rho_r \leq \frac{\rho_{ALL}}{2+F}$. Substituting them into Eqs. (10)-(17) and following the steps of proving Proposition 2, we have the following asymptotic ABEP of FD-TWRC-SM with unequal average SNRs at the nodes.

**Lemma 5.** When $2\rho_i + \rho_r = \rho_{ALL}$, the asymptotic ABEP of FD-TWRC-SM systems is computed by

$$ABE_{FD,PA} \leq ABE_{FD,PA} + ABE_{FD,PA}, \tag{36}$$

where

$$L_1(F) = \frac{E^{\mu(1 - \mu)}}{(2+F)^{-N_{R,r}+1}} \left( q_1(1 - \mu) \right) \left( 2 + F \right)^{N_{R,r}}, \tag{39}$$

$$L_2(F) = \frac{E^{N_{R,2}}}{(2+F)^{-N_{R,2}}+1} \left( 2 + F \right)^{N_{R,2}}, \tag{40}$$

$G_1$, $G_2$, $K_1$, and $K_2$ are computed by (24), (25), (28), and (29), respectively.

It is observed that the power allocation does not affect the diversity order of the system, which is expressed by Eqs. (37)
and (38), whereas the power allocation affects the coding gain. By using Lemma 5, an optimal PA factor is computed by Proposition 4.

**Proposition 4.** The optimal PA factor is computed as follows.

When $N_{R,r} = N_{R,2}$,

$$F = N_{R,2}^{1/2} \sqrt{A_{r2}A_{1r}^{-1}}, \quad (41)$$

where

$$A_{1r} = N_{R,r} \sum_{q_1=0}^{N_{R,r}} G_1 K_1(q_1) \rho_{All}^{-N_{R,r} + q_1(1-\mu)}, \quad (42)$$

$$A_{r2} = 2N_{R,2} \sum_{q_2=0}^{N_{R,2}} G_2 K_2(q_2) 2^{-q_2(1-\mu)} \rho_{All}^{-N_{R,2} + q_2(1-\mu)}. \quad (43)$$

When $N_{R,r} > N_{R,2}$, the optimal $F$ is the positive real root of Eq. (44), which can be represented in a closed form when $N_{R,r} \leq 4$. If $N_{R,r} > 4$, the positive real root of Eq. (44) can be obtained by Newton-Raphson method [61].

$$F^{N_{R,r}+1/2 + (2+F)^{N_{R,r}-N_{R,2}}} = A_{r2}A_{1r}^{-1}. \quad (44)$$

When $N_{R,r} < N_{R,2}$, the optimal $F$ is the positive real root of Eq. (45), which can be represented in a closed form when $N_{R,2} \leq 4$. If $N_{R,2} > 4$, the positive real root of Eq. (45) can be obtained by Newton-Raphson method [61].

$$F^{N_{R,2}+1/2 + (2+F)^{N_{R,2}-N_{R,r}}} = A_{r2}A_{1r}^{-1}. \quad (45)$$

**Proof:** See Appendix D.

V. NUMERICAL RESULTS

A. Verification

The aim of this subsection is to substantiate the analytical results obtained in this paper through numerical results. Three case studies are considered: i) ABEP upper bounds over i.i.d. Rayleigh channels. ii) SNR threshold for the selection between HD and FD under the same spectrum efficiency. iii) Optimal PA factor under a given total $\rho_{All}$.

1) Verification of ABEP upper bounds and SNR threshold for HD/FD selection: In Fig. 4, for 3bpcu TWRC-SM and HD-TWRC-SM systems the analytical upper bounds on the ABEP, Monte Carlo simulation results for $10^6$ channel realizations, and the asymptotic ABEPs are plotted where $N_1 = N_2 = 4$ for both FD and HD systems and the average SNR is $\rho_r = \rho_r = \rho$. In FD-TWRC-SM, we use $M_1 = M_2 = 2$, whereas in HD-TWRC-SM we use $M_1 = M_2 = 16$. The analytical upper bounds on the ABEPs of FD-TWRC-SM are computed by (10) using (14) and (16), whereas the asymptotic ABEPs of HD-TWRC-SM are computed by (30). It is observed in Fig. 4 that as the SNR increases, the difference between the analytical upper bound on the ABEP and the exact ABEP becomes negligible.

Moreover, the analytical SNR threshold given in (31) is also plotted using dashed lines. It is observed that the proposed SNR threshold for the selection between FD/HD agrees well with the point of intersection between the asymptotic ABEPs of FD and HD systems. Then this SNR threshold (31) can be utilized to decide whether FD transmission or HD transmission should be adopted to enhance the performance of TWRC-SM systems.

In section II, we showed an alternative constant SIR model [51]. The ABEP of FD-TWRC-SM systems under a constant SIR model is plotted in Fig. 5. It is observed that under the constant SIR model, there exists an ABEP floor that decreases with an increasing SIR $\beta$ as consistent with the result in [51].

$$ABEP_{1r,FD,PA} \leq \sum_{q_1=0}^{N_{R,r}} G_1 K_1(q_1) L_1(F) \rho_{All}^{-N_{R,r} + q_1(1-\mu)} \quad (37)$$

$$ABEP_{2r,FD,PA} \leq \sum_{q_2=0}^{N_{R,2}} G_2 K_2(q_2) L_2(F) \rho_{All}^{-N_{R,2} + q_2(1-\mu)} \quad (38)$$
properties of FD-TWRC-SM systems for various numbers of various system parameters. Especially, we investigate diversity in a realistic system, then the HD system will be a better order is higher than 10. We find that a good SI cancellation is a prerequisite to employ the best ABEP can be achieved at $F_{\text{opt}}$ under different $N$. However, the best ABEP is achieved at $F < 0$ or $F > 0$ depending on the relationship between $N_{R,2}$ and $N_{R,1}$.

2) Verification of optimal power allocation: The optimal PA factors computed by Proposition 4 and ABEP upper bounds of both FD and HD systems computed by (10)-(17) are given in Fig. 6, with 4bpcu data rate, $N_1 = N_2 = 4$ and $M_1 = M_2 = 4$. It is observed that the optimal PA factors $F$ can minimize the ABEP of FD-TWRC-SM systems. It is observed that the best ABEP can be achieved at $F = 0$ when $N_{R,2} = N_{R,1}$. However, the best ABEP is achieved at $F < 0$ for $F > 0$ depending on the relationship between $N_{R,2}$ and $N_{R,1}$.

B. System performance under various system parameters

First, we compare the ABEPs of FD-TWRC-SM systems under different $\mu$ in Fig. 7 with $N_{R,i} = N_{R,r} = 4$. In FD-TWRC-SM systems, we use $N_i = 4$ and $M_i = 2$, whereas $N_i = 4$ and $M_i = 16$ are used in HD-TWRC-SM systems. We find that a good SI cancellation is a prerequisite to employ FD transmissions in the TWRC-SM system and the diversity order is $\mu \min\{N_{R,i}, N_{R,r}\}$. When $\mu < 0.4$, the ABEP is higher than $10^{-5}$ even at a 40dB SNR, which is unacceptable in a realistic system, then the HD system will be a better choice than the FD system.

Then, we analyze the performance of FD-TWRC-SM for various system parameters. Especially, we investigate diversity properties of FD-TWRC-SM systems for various numbers of receive antennas. Also, we evaluate the ABEPs of FD-TWRC-SM systems and then compare them for different numbers of receive antennas at a given data rate constraint. Furthermore, we analyze the impact of an increasing number of transmit antennas on the ABEP at a given signal constellation diagram. Firstly, we investigate the impact of the number of receive antennas on the ABEP at a 3bpcu data rate in Fig. 8 with $M_1 = M_2 = 2$ and $N_1 = N_2 = 4$. It is observed that the ABEP decreases by increasing $N_{R,i}$ and/or $N_{R,r}$. However, the system performance can not be improved significantly by solely increasing $N_{R,r}$ or $N_{R,i}$. To improve the diversity performance of FD-TWRC-SM systems, we need to increase both $N_{R,r}$ and $N_{R,i}$ simultaneously.

In 5G cellular networks, energy efficient massive MIMO will be employed, where hundreds of antennas are utilized for transmitting gigabit-level wireless traffic [57]. When $N_i > 16$, the number of transmit antennas at R is greater than 256, and the proposed FD-TWRC-SM system can be seen as a two-way FD massive MIMO. Since SM system is a promising candidate in low-complexity massive MIMO implementations [58], we investigate the impact of the increasing transmit antennas and evaluate the potential performance gains of FD-TWRC-SM systems. With a data rate constraint, the ABEPs against SNR are plotted in Fig. 9. We have the following observations.
1) At a fixed data rate, the ABEP of FD-TWRC-SM systems decreases by increasing \( N_i \). As a specific configuration of the FD-TWRC-SM system, the FD-TWRC-single input multiple output (SIMO) system, where \( N_i = 1 \), performs as the worst one under a given data rate.

2) The ABEP of FD-TWRC-SM systems with BPSK signal constellation diagram is nearly the same as FD-TWRC-SSK systems at the same data rate. Similar phenomenon can be found in single link SM transmissions [7, Figs. 9-10]. Considering both ABEP and the size of the transmit antenna array, BPSK can be seen as the optimal choice of signal constellation.

With \( M_i = 2 \), the ABEPs against SNR are plotted in Fig. 10 with \( N_{R,r} = N_{R,i} = 4 \). It is observed that with a given signal constellation diagram, the SNR loss, which is caused by increasing \( N_i \), is quite small. According to (28), (29), (24), and (25), we can see that the number of transmit antennas \( N_i \) is irrelevant to \( K_1 \) and \( K_2 \) at a fixed \( M_i \), whereas it impacts \( G_1 \) and \( G_2 \) simultaneously. Therefore, using \( N_i = 2 \) as a benchmark, the ABEP losses caused by increasing the transmit antennas of the first and the second hops are respectively computed by \( A_{BEPA_i} = \frac{G_1}{G_2} \) and \( \Delta A_{BEPA_i} = \frac{G_2}{N_{R,r}N_{R,i}} \). Since the diversity orders of both hops in FD-TWRC-SM systems are respectively \( \mu_{R,r} \) and \( \mu_{R,i} \), in the high SNR regime, we obtain approximate SNR losses of both hops caused by adding transmit antennas as \( \Delta \rho_{1r} = (G_1/G_{1,N_i=1})^{\mu_{R,r}/2} \) and \( \Delta \rho_{2r} = (G_2/G_{2,N_i=1})^{\mu_{R,i}/2} \), which are plotted in Fig. 11. We obtain the following observations.

1) For BPSK signal constellation and \( N_R = 4 \), the SNR loss is less than 4 dB in general when the data rate is increased by 3bpcu. When \( N_R = 2 \), the SNR loss is less than 10 dB. Thus, in a massive MIMO system with a less number of receive antennas in comparison with the number of transmit antennas [58], a \( \log_2 N_1 \)

---

Footnote:

2Although the SNR loss computed by using diversity order is not precise, it allows us to get very simple analysis on the impact of adding transmit antennas on the ABEP.

---

C. Optimal selection between HD and FD modes

The SNR thresholds against \( \mu \) are illustrated in Fig. 12. In the 3bpcu TWRC-SM systems, we use \( N_1 = N_2 = 4 \) and \( M_1 = M_2 = 2 \) for FD-TWRC-SM, and \( N_1 = N_2 = 4 \) and \( M_1 = M_2 = 16 \) for HD-TWRC-SM, respectively. In the 5bpcu TWRC-SM systems, we use \( N_1 = N_2 = 16 \) and \( M_1 = M_2 = 2 \) for FD-TWRC-SM, and \( N_1 = N_2 = 16 \) and \( M_1 = M_2 = 64 \) for HD-TWRC-SM, respectively. Then we have the following observations.

1) It is observed that with a greater \( \mu \), the FD node is subject to a lower residual SI. Since the SNR threshold becomes higher, it is more beneficial to select FD transmissions in both low and modest SNR regimes. In particular, when \( \mu > 0.8 \), the SNR threshold is greater
than 60 dB, so that FD is always a better choice when \( \rho \leq 60 \) dB.

2) Under the same data rate constraint, we have

\[
2 \log_2 M_{\text{FD},i} N_i = \log_2 M_{\text{HD},i} N_i,
\]

and therefore

\[
M_{\text{HD},i} = M_{\text{FD},i}^2 N_i.
\]

When \( N_i \) increases, \( M_{\text{HD},i} \) becomes so large that the Euclidean distance of adjacent signal symbols is very small and the performance of HD systems is deteriorated significantly. Specifically, when \( N_i = 16 \) and \( M_{\text{FD},i} = 2 \), the signal constellation diagram at R of the HD systems is 4096-QAM. In this case, as long as \( \mu > 0.55 \), the threshold in 5bpcu is always greater than 40 dB. Thus, we can say that for a massive MIMO system, the FD-TWRC-SM almost always works better than its HD counterpart.

3) With a less number of receive antennas, it is more beneficial to select the FD transmissions due to a higher SNR threshold. Similar phenomenon can be observed in Fig. 4.

D. Optimal power allocation

The optimal PA factors against \( \mu \) are illustrated in Fig. 13. In the 3bpcu TWRC-SM systems, we use \( N_1 = N_2 = 4 \) and \( M_1 = M_2 = 2 \). In the 4bpcu TWRC-SM systems, we use \( N_1 = N_2 = 4 \) and \( M_1 = M_2 = 4 \). Then, we have the following observations.

1) When \( N_{R,r} > N_{R,i} \), \( F \) becomes large and greater than 5dB in general. The diversity order of the first hop is higher than that of the second hop, so that the ABEP of the second hop is the bottleneck of the overall ABEP. Therefore, we need to allocate more power to the second hop to obtain an optimal performance. Conversely, when \( N_{R,r} < N_{R,i} \), we need to allocate more power to the first hop.

2) The optimal PA factor \( F \) increases with the data rate. The gap becomes more significant when \( N_{R,r} < N_{R,i} \).

3) When \( N_{R,r} = N_{R,i} \), the optimal PA factor \( F \) is independent of SNR. However, in other two cases, the total SNR should be taken into account carefully. For instance, the gap between \( F \)s under 40dB and 50dB \( \rho \)ALLs is about 3dB when \( N_{R,r} \neq N_{R,i} \).

4) As \( \mu \) increases, \( F \) behaves differently under different conditions. When \( N_{R,r} = N_{R,i} \), \( F \) seems to be almost independent of \( \mu \). When \( N_{R,r} > N_{R,i} \), \( F \) increases with an increasing \( \mu \). When \( N_{R,r} < N_{R,i} \), \( F \) decreases with an increasing \( \mu \).

E. Comparison with single optimal antenna selection

As another category of MIMO systems with a single transmit RF chain, the optimal antenna selection (OAS) system has been widely investigated and introduced into TWRC transmission [56], [59]. In this section, we compare the performance of the proposed FD-TWRC-SM system with that of the FD-TWRC-OAS system. In the FD-TWRC-OAS system, optimal transmit antennas in term of the received signal strength of the intended signal are selected to transmit QAM signals in the first hop and the max-min antenna selection algorithm proposed in [56, Algorithm 1] is employed in the second hop. For sake of fair comparisons, the transmission rule of FD-TWRC-OAS is identical with that of the proposed FD-TWRC-SM system. In [56], \( S_i \)s transmit their respective signals to R in two time blocks successively, whereas in the considered FD-TWRC-OAS system in this subsection, both \( S_i \)s transmit signals simultaneously in a single time block, as consistent with Fig. 2.

The ABEP comparison of the proposed FD-TWRC-SM system with the FD-TWRC-OAS system are plotted in Fig. 14 where \( N_{R,i} = N_{R,r} = 4 \). Since it is intractable to analytically derive the ABEP of the FD-TWRC-OAS system due to the
complex distribution of the channel amplitude after transmit antenna selection and the superposition of two independent signals from both sources, we plot the ABEP of the FD-TWRC-OAS system by using Monte Carlo simulations. Under 3bpcu configuration, we use $M_t = 2, N_t = 4$ for the FD-TWRC-SM system, and $M_t = 8, N_t = 4$ for the FD-TWRC-OAS system. Whereas under 4bpcu configuration, we use $M_t = 4, N_t = 4$ for the FD-TWRC-SM system, and $M_t = 16, N_t = 4$ for the FD-TWRC-OAS system. In the OAS system, both the transmitter and the receiver need to know the CSI, but in the SM system, the CSI is only required by the receiver. It is found in Fig. 14 that the FD-TWRC-OAS system has a higher diversity order than the FD-TWRC-SM system. Nevertheless, under typical configurations, the FD-TWRC-SM performs better than the FD-TWRC-OAS system because the information that is mapped onto the spatial constellation can efficiently reduce the size of the signal constellation.

VI. CONCLUSIONS

In this paper, we have proposed a FD-TWRC-SM with the optimal ML detector employed at each node. Firstly, a tight ABEP upper bound of the referred system has been derived in the closed form expression under i.i.d. Rayleigh fading channels. From the analytical ABEP analysis, we have found that the diversity order of the FD-TWRC-SM system is determined by the quality of SI cancellation. Then, we have conducted an extensive simulation campaign to evaluate the system performance. We have found that the proposed FD-TWRC-SM system is a promising candidate in low-complexity TWRC massive MIMO implementations because of its low SNR loss caused by multiplexing gain that is provided by adding transmit antennas. In addition, both HD-TWRC-SM and FD-TWRC-SM systems have been compared in terms of the ABEP. The exact SNR threshold, below which a better performance can be achieved by FD-TWRC-SM over HD-TWRC-SM, is analytically derived in a closed form. It has been observed that the FD-TWRC-SM with a reasonably good SI cancellation works better than its HD counterpart. Moreover, we have investigated the power allocation among sources and relay by deriving the optimal PA factor in a closed form. We have found that when $N_{R,r} > N_{R,i}$, more power needs to be allocated to the second hop to achieve an optimal performance. Whereas when $N_{R,r} < N_{R,i}$, more power needs to be allocated to the first hop. Finally, the SM system has been compared with the OAS system in FD-TWRC scheme. We have found that under typical configurations, the FD-TWRC-SM outperforms the FD-TWRC-OAS because the information that is mapped onto spatial constellation can efficiently reduce the size of the signal constellation.

However, since there is no any research on the modeling of the residual SI in the SM context, we will investigate the practical SI cancellation schemes in our future works. Some other SM systems will be incorporated into the FD-TWRC scheme, e.g., coded SM and generalised SM schemes. We will also investigate other types of arbitrary configurations with $N_r \neq N_1 N_2$, and $M_2 \neq M_1 M_2$. Moreover, we will investigate on derivation of a closed form ABEP of the FD-TWRC-OAS system.

APPENDIX

A. Proof of Proposition 1

Firstly, with i.i.d. channels, the ABEP is irrelevant to the specific antennas that are chosen to transmit signals at $S_j$. Without loss of generality, letting $n_1 = n_2 = 1$, (9) can be rewritten as (46). In the high SNR regime, the ABEP of the transmission is determined by the hop having a worse performance [56]. Therefore, two cases of error are considered, i.e., the errors that occur in the first and second hops. When the error occurs in the first hop, two cases have to be taken into account. First, $I_2$ is wrongly detected and therefore $I_1$ is not a candidate of the detection in the second hop. Second, $I_2$ is rightly detected while $I_1$ is a candidate of the detection in the second hop. Therefore, a detection error of $I_1$ might occur when i) $I_2$ is wrongly detected in the first hop; ii) $I_2$ is correctly detected but $I_1$ is wrongly detected in the first hop; or iii) both $I_1$ and $I_2$ are correctly detected in the first hop but $I_1$ is wrongly detected in the second hop. Then (46) is rewritten as (47).

\[
\begin{align*}
\text{ABEP}_{I_1 \neq I_1, I_2 = I_2} & = M_1 M_2 \log_2(N_1 M_1) \\
& + \sum_{I_2 = (1, 1)} D_H(\hat{n}_1, \hat{n}_1, n_1, m_1) PEP(m_1, 1, m_2, 1, \hat{n}_1, \hat{n}_1, \hat{n}_2, \hat{n}_2, \hat{n}_1, \hat{n}_1) \\
& + \sum_{I_2 = (1, 1)} D_H(\hat{n}_1, \hat{n}_1, n_1, m_1) PEP(m_1, 1, m_2, 1, \hat{n}_1, \hat{n}_1, \hat{n}_2, \hat{n}_2, \hat{n}_1, \hat{n}_1) \\
\text{ABEP}_{I_1 = I_1, I_2 = I_2} & = M_1 M_2 \log_2(N_1 M_1) \\
& + \sum_{I_2 = (1, 1)} D_H(\hat{n}_1, \hat{n}_1, n_1, m_1) PEP(m_1, 1, m_2, 1, \hat{n}_1, \hat{n}_1, \hat{n}_2, \hat{n}_2, \hat{n}_1, \hat{n}_1) \\
& + \sum_{I_2 = (1, 1)} D_H(\hat{n}_1, \hat{n}_1, n_1, m_1) PEP(m_1, 1, m_2, 1, \hat{n}_1, \hat{n}_1, \hat{n}_2, \hat{n}_2, \hat{n}_1, \hat{n}_1) \\
\end{align*}
\]
Further simplification of \( ABEPI_{i \neq j} \), \( ABEPI_{i \neq j} \), \( ABEPI_{i = j} \) and \( ABEPI_{i = j} \) can be obtained as follows:

1) When \( I_2 \) is wrongly detected by \( R \) in the first hop, i.e., \( I_2 \neq I_2 \), according to (6), we have (48).

By substituting (50) into (49) and using some algebraic manipulations, we obtain (51).

For any bit mapping, \( D_H(\hat{m}_1, \hat{n}_1, n_1, m_1) = D_H(\hat{m}_1, n_1, 1, m_1) + D_H(\hat{m}_1, m_1, 1) \). Therefore, when \( \hat{n}_1 = 1 \), \( D_H(\hat{m}_1, \hat{n}_1, 1, m_1) = D_H(\hat{m}_1, m_1) \).

When \( \hat{n}_1 \neq 1 \), because \( \sum_{n_1 = 1}^{N_1} \sum_{n_2 = 1}^{N_2} D_H(\hat{n}_1, n_1, 1) = N_1 \log_2 N_1 + D_H(\hat{m}_1, m_1) \). Similarly, with i.i.d. channels, the Euclidean distance of any pair of channels coefficients is the same on average. Thus (12) can be readily obtained after some algebraic manipulations.

3) When both \( I_1 \) and \( I_2 \) are correctly detected at \( R \) in the first hop, i.e., \( I_1 = I_1, I_2 = I_2 \), the detection error occurs only in the second hop, for which we have (52), and \( ABEPI_{i = j} = 0.5 \times \Pr(I_2 = I_2) \). Likewise, (13) can be obtained.

B. Proof of Lemma 1

The residual SI and noise are both complex Gaussian distributed with variances of \( h_{1, r}^2 \) and \( h_{2, r}^2 \), respectively. If \( (m_1, m_2, m_2, n_2) \neq (\hat{m}_1, \hat{n}_1, \hat{m}_2, \hat{n}_2) \), (from (1)), the transmission from \( S_1 \) to \( R \) is equivalent to the SM transmission with an average SNR of \( \rho_{o,i} = \frac{\sqrt{\rho_o^2 h_{1, r}^2}}{\sqrt{\rho_o^2 h_{1, r}^2} + \sqrt{\rho_o^2 h_{2, r}^2} + 1} \). According to (50) and the steps provided in [8, Section IV], \( PEP_{1, r} \) between \( (\hat{m}_1, \hat{n}_1, m_2, n_2) \) and \( (m_1, \hat{n}_1, m_2, n_2) \) under given \( h_{1, r} \) and \( h_{2, r} \) is computed by

\[
PEP_{1, r, h_{1, r}, h_{2, r}, m_2, n_2} = Q\left(\sqrt{d_{1, r}^2/2}\right),
\]

where \( d_{1, r} \) is defined as (55). Since the elements of \( h_{1, r} \) and \( h_{2, r} \) are all complex Gaussian distributed and \( d_{1, r} \) is a weighted sum of the norms of \( h_{1, r} \) and \( h_{2, r} \), the elements of \( \sqrt{\rho_o^2 h_{1, r}^2} [k, n_1, x_1 | m_1] + \sqrt{\rho_o^2 h_{2, r}^2} [k, n_2, x_2 | m_2] - \sqrt{\rho_o^2 h_{1, r}^2} [k, \hat{n}_1, \hat{x}_1 | \hat{m}_1] - \sqrt{\rho_o^2 h_{2, r}^2} [k, \hat{n}_2, \hat{x}_2 | \hat{m}_2] \) are also complex Gaussian distributed. It is observed that the variance of \( \sqrt{\rho_o^2 h_{1, r}^2} [k, n_1, x_1 | m_1] \) and \( \sqrt{\rho_o^2 h_{2, r}^2} [k, \hat{n}_1, \hat{x}_1 | \hat{m}_1] \) depends on whether \( \hat{n}_1 = n_1 \) or not. To be specific, if \( \hat{n}_1 = n_1 \), we have (56). Else if \( \hat{n}_1 \neq n_1 \), we have (57), where \( D[\cdot] \) denotes the variance. Similar discussion is applied to \( D[\sqrt{\rho_o^2 h_{2, r}^2} [k, n_2, x_2 | m_2] - \sqrt{\rho_o^2 h_{2, r}^2} [k, \hat{n}_2, \hat{x}_2 | \hat{m}_2]] \).

Since the real part and imaginary part of \( h_{1, r} \) and \( h_{2, r} \) are all Gaussian distributed with a variance of 0.5, \( d_{1, r} \) follows Chi-square distribution with a freedom degree of \( 2N_{t, r} \), i.e.,

\[
\frac{d_{1, r}^2}{2} \sim \chi^2_{2N_{t, r}},
\]

where \( \nu \) is defined in (15). Following the steps of [60, Eqs. (61)-(65)], we have

\[
PEP_{1, r, m'} = E_{m'} \left[ PEP_{1, r, h_{1, r}, h_{2, r}} \right] = \langle N_{r, t, v} \rangle,
\]

based on which (14) can be obtained.
C. Proof of Proposition 2

Using \( R(N_{\text{r}}, \kappa) = 4^{-N_{\text{r}}C_{2N_{\text{r}}-1}} \), and some algebraic manipulations of (14) and (16), the asymptotic \( P_{\text{EP}} \) and \( P_{\text{RP}} \) can be obtained as

\[
P_{\text{EP}} = \frac{\sum_{q=0}^{N_{\text{r}}} K_1(q)\rho^{-N_{\text{r},q}}} {M_1 M_2 v_0 N_{\text{r},r}},
\]

\[
P_{\text{RP}} = \frac{\sum_{q=0}^{N_{\text{r},2}} K_2(q)\rho^{-N_{\text{r},2,q}}} {M_1 \xi_0 N_{\text{r},2}},
\]

where \( K_1(q), K_2(q), v_0, \) and \( \xi_0 \) are defined in (28), (29), (26), and (27), respectively. We define a notation \( \hat{\phi} = \phi - \rho \), and then we can obtain (41)-(45) by typical approaches for solving the polynomial equations.

D. Proof of Proposition 4

To prove this proposition, we need to solve the equation \( \partial_{\text{PA}} P_{\text{EP}} = 0 \). However, the optimal PA factor is difficult to derived in a closed form based on (37) and (38). In order to derive the optimal power allocation factor, the following upper bound on \( L_1(F) \) and \( L_2(F) \) are employed.

\[
L_1(F) \leq (2 + F)^{N_{\text{r},r}},
\]

\[
L_2(F) \leq \left( \frac{F}{2 + \tau} \right)^{N_{\text{r},2}} - q_2(1 - \mu),
\]

In (64), the upper bound of \( L_1(F) \) is given as the maximum sum quantity of the SNRs. Whereas in (65), if we also use the maximum sum quantity of the SNRs, we have \( L_2(F) \leq \left( \frac{F}{2 + \tau} \right)^{N_{\text{r},2}} - q_2(1 - \mu) \leq \left( \frac{F}{2 + \tau} \right)^{N_{\text{r},2}} - q_2(1 - \mu) \) is a tighter upper bound than (65). In the following, the optimal PA factor is analyzed based on (65). Substituting Eqs. (64) and (65) respectively into Eqs. (37) and (38), we obtain (66) and (67). Since our target is to minimize \( ABEP_{1,F,D,PA} + ABEP_{2,F,D,PA} \), we have (68), where \( A_{1r} \) and \( A_{2r} \) are computed by (42) and (43), respectively. Some simple algebraic manipulations lead to

\[
F^{N_{\text{r},2} + 1}(2 + F)^{N_{\text{r},r} - N_{\text{r},2}} = A_{1r} A^{-1}_{2r},
\]

and then we can obtain (41)-(45) by typical approaches for solving the polynomial equations.
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