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Outage Probability of MIMO Relaying Full-Duplex System with Wireless Information and Power Transfer

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***Abstract*—In this paper, we consider a full duplex relaying multi input multi output (MIMO) system where the relay has no fixed energy supply but replenishes energy from radio frequency (RF) signals transmitted from source. At the transmitter, transmit antenna selection (TAS) and maximal ratio transmission (MRT) are employed. Whereas, at the second hop, both selection combining (SC) and maximal ratio combining (MRC) techniques are used. In addition, the decode-and-forward relaying protocol is applied. We derive the expressions of outage probability ($\mathcal{OP}$) of the simultaneous information and energy transfer in Rayleigh fading relay channel. Numerical results are presented to demonstrate the validity of our analysis and to show the advantages of full duplex relaying MIMO system.**

***Index Terms*—Full-duplex, wireless power transfer, decode-and-forward, throughput, outage probability.**

I. INTRODUCTION

Multi-hop communication systems have been considered as a promising solution to enhance the throughput and improve power efficiency. The relay systems not only extend the coverage of wireless systems [1] but also overcome channel fading effect. MIMO technique constituting a key technology for modern wireless communications has a trade-off between superior error performance and higher data rate. On the other hand, TAS is a simple effective method that can provide full diversity order and improve the performance of wireless network systems [2].

Radio frequency (RF) energy transfer and harvesting techniques have recently become alternative methods to power the next generation wireless networks [3]. They are becoming promising solutions to power energy-constrained wireless networks, such as wireless sensor networks where limited lifetime largely confines the network performance. Moreover, one of the main challenges in fifth generation (5G) wireless networks is to improve the energy efficiency of battery-constrained wireless devices [4].

In recent years, the advantages of energy harvesting (EH) techniques have attracted a lot of attention from researchers. Particularly, the combination of relaying protocols and the EH can increase the system lifetime. The downlink hybrid information and energy transfer with massive MIMO techniques is analyzed in [5] where the system simultaneously sends information and energy to information users and energy users. In [6], the authors consider two multiple-antenna transceivers exchanging information through a relay assisted network with single-carrier communication scheme. The relay nodes use harvest-then-forward protocol to get the energy from surrounding environment and utilize this energy to forward their received messages. The authors in [7] derive a closed-form expression of the outage probability of dual-hop decode-and-forward (DF) relaying network which utilizes a time switching-based relaying mechanism. The outage probability of the dual hop multiple antenna relying system transferring wireless power is investigated in [8]–[10]. In [8], the authors propose a dual-hop multiple antenna amplify-and-forward relaying system in the presence of interference using both fixed-gain and variable-gain relaying schemes, then give the exact closed-form expressions of the outage probability.

Nowadays, the topics of relaying communication are widely studied not only in the half-duplex transmission systems but also in the full-duplex transmission systems. Full-duplex relaying (FDR) technique allows relay node to receive and transmit signal simultaneously on the same frequency band. The advantage of FDR is to double the spectral efficiency compared with haft duplex relaying (HDR). Hence, FDR is considered as an efficient solution to overcome the shortcoming of HDR [11]. Combining wireless power transfer with the full-duplex relaying protocol is also a good method to prolong the network lifetime of wireless networks.

Motivated by these advantages, in this paper, we focus on a source-relay-destination dual-hop scenario where the relay is powered via harvested energy from RF signal, and study the effect of FDR on the outage performance and the throughput of a RF energy harvesting relaying system. Specially, we investigate the combination of TAS and MRT schemes in the first hop whereas in the second hop we analyze the combination of SC and MRC schemes. The main contributions of the paper are summarized as follows:

- We propose a MIMO-FDR system and then analyze its performance by deriving the closed-form outage probability expressions for the cases of transmit antenna selection (TAS) and maximum ratio transmission (MRT) schemes at the transmitter; corresponding to the transmitter we employ selection combining (SC), maximum ratio combining (MRC) schemes at the receiver.
- Especially, we consider the impact of loopback interference on the outage performance of FDR systems.

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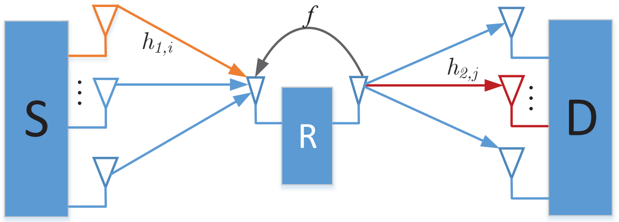

Fig. 1. Wirelessly powered MIMO relaying Full-Duplex Networks.

Moreover, we conduct Monte-Carlo simulations to verify the correctness of analytical results.

The rest of this paper is organized as follows. Section II describes the full-duplex relaying MIMO system model. Derivation of the outage probability of the proposed protocol is presented in Section III-A, III-B, III-C. Section IV shows the numerical results obtained from both analysis and simulation. Finally, some conclusions are given in Section V.

II. SYSTEM MODEL

The proposed dual-hop FDR system is illustrated in Fig. 1. Source (S) and destination (D) are equipped with N_{S} and N_{D} antennas, respectively. In order to enable the FDR technique, the relay (R) is equipped with two antennas, i.e., one for reception and one for transmission during the information transmission phase[1]. According to antenna theory, the elements of the antenna array are required to be spaced at a distance of half a wavelength apart. Hence, two antennas of R must be separated at least half of wavelength to avoid mutual coupling effect between antennas [13]. The S and the D communicate to each other through an intermediate R support. There is no direct link from S $\longrightarrow$ D due to far distance or deep shadow-fading. It is also assumed that the relay only has limited power supply, and relies on the external charging through the harvested energy from source transmission [14]. The energy harvested during the energy harvesting phase is stored in a super-capacitor[2]. Specifically, all the harvested energy during EH phase is consumed by the R within the signal transmission process from S to D. A perfect transferring circuit and negligible power consumption in rectifier and energy storage are assumed.

We consider that all wireless links exhibit frequency non-selective Rayleigh block fading, i.e., channel coefficients are constant during one block time T and independent and identically distributed (i.i.d.) from one slot to the next. In addition, it is assumed that the CSI is available at any terminals in the network. Let us denote h_{SR} and h_{RD} as channel coefficients of the n^{th} antenna at the S to reception antenna of R and from transmission antenna of R to m^{th} antenna at the D, respectively. As all channel coefficients are Rayleigh-distributed, the channel gains such as $|h_{\mathsf{SR}}|^2$ and $|h_{\mathsf{RD}}|^2$ are exponential random variables (RVs) with mean values of λ_{1i} and λ_{2j}, respectively. In addition, $|f|^2$ is exponentially distributed with mean λ_3 which is a key parameter related to the strength of the loopback interference.

Now, we describe the communicating process from source to destination of the full duplex communication system with energy harvesting RF as follows. Under the time switching (TS) energy harvesting model [14][3], the communication from the S to the D is divided into two consecutive time slots including energy transmission, information transmission, and information reception. Let T denote the time block of an entire communication period in which the information is transmitted from S to D. At every T period, the first αT amount of time is used for energy harvesting at R while the remaining $(1-\alpha)T$ amount of time is used for information transmission and reception, where α denotes the fraction of the block time, $0 \leq \alpha \leq 1$.

In the first time slot, the relay harvests an amount of wireless energy from the S and then converts into a voltage of direct current (DC) by using appropriate circuits. In the second time-slot, the received signal y_{R} at R is given by

$$y_{\mathsf{R}}(k) = \sqrt{P_{\mathsf{S}}}h_{\mathsf{SR}}x(k) + \sqrt{P_{\mathsf{R}}}f\,\tilde{x}(k) + n_{\mathsf{R}}(k), \tag{1}$$

where P_{S}, P_{R} are the average transmitted power of the S, R, respectively. $x(k)$ and $\tilde{x}(k)$ are modulated signal and received signal of k^{th} symbols at the S and R, respectively. $n_{\mathsf{R}}(k)$ is additive white Gaussian noise (AWGN) at R with the zero mean and variance σ_{R}^2, i.e, $\mathcal{CN}(0, \sigma_{\mathsf{R}}^2)$. In addition, f denotes the loopback interference channel. For mathematical tractability, we assume that $n_{\mathsf{R}}(k)$ is very smaller than $\sqrt{P_{\mathsf{R}}}f\,\tilde{x}(k)$, i.e., the noise at the R can be ignored [18]. We should be reminded that some mitigation self interference cancellation schemes are proposed in [16].[4]

According to the full duplex DF protocol, R decodes the original signal and then regenerates the signal at the same time. Then, the received signal at D can be expressed as

$$y_{\mathsf{D}}(k) = \sqrt{P_{\mathsf{R}}}h_{\mathsf{RD}}\tilde{x}(k) + n_{\mathsf{D}}(k), \tag{2}$$

where $n_{\mathsf{D}}(k)$ is AWGN at D with the zero mean and variance σ_{D}^2, i.e, $\mathcal{CN}(0, \sigma_{\mathsf{D}}^2)$. We assume that transmission and reception occur in orthogonal subspaces so that the signals are not correlated.

From (1) and (2), we have the instantaneous signal-interference-noise-ratios (SINRs) of S $\rightarrow$ R and R $\rightarrow$ D links as

$$\gamma_{\mathsf{SR}} = \frac{P_{\mathsf{S}}|h_{\mathsf{SR}}|^2}{P_{\mathsf{R}}|f|^2 + \sigma_{\mathsf{R}}^2}. \tag{3}$$

$$\gamma_{\mathsf{RD}} = \frac{P_{\mathsf{R}}|h_{\mathsf{RD}}|^2}{\sigma_{\mathsf{D}}^2}. \tag{4}$$

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[1] We note that FD radio prototypes equipped with a circulator can transmit and receive signals simultaneously with a single antenna [12].

[2] Please note, this is also known in the literature [3], [15] as harvest-use architecture as opposed to the harvest-store-use architecture

[3] The proposed analysis approach can be applied for the power spitting EH model.

[4] Mitigation self interference schemes: natural isolation, time-domain cancellation, and spatial suppression.

As specified in the DF protocol, it is required that both relay and destination to decode the entire codeword without errors, which results in the minimum of two mutual informations, i.e., the system quality depends on the link having the lowest SNR. Therefore, we have the end-to-end SINR of the system as

$$\gamma_{\mathsf{e2e}} = \min\left(\gamma_{\mathsf{SR}}, \gamma_{\mathsf{RD}}\right). \tag{5}$$

In the following, we will a detailed analysis of the outage probability for three combined schemes: TAS/SC, TAS/MRC, and MRT/MRC.

III. OUTAGE ANALYSIS

A. The TAS/SC scheme

The technical performance of TAS/SC is evaluated by the $\mathcal{OP}$. The harvested energy from TAS technique during the amount of time αT is expressed as [14]

$$E_h = P_{\mathsf{S}}\eta\alpha T \max_{i=1,\ldots,N_{\mathsf{S}}} |h_{1,i}|^2, \tag{6}$$

where $0 < \eta \leq 1$ is the energy conversion efficiency.

Assuming that all harvested energy during the energy harvesting phase is stored in a supercapacitor and then fully consumed by the relay to forward the source signal to the destination, the transmitted power at R is

$$\begin{aligned} P_{\mathsf{R}} =& \frac{\alpha\eta P_{\mathsf{S}}}{(1-\alpha)} \max_{i=1,\ldots,N_{\mathsf{S}}} |h_{1,i}|^2 \\ =& \phi P_{\mathsf{S}} \max_{i=1,\ldots,N_{\mathsf{S}}} |h_{1,i}|^2, \end{aligned} \tag{7}$$

where $\phi = \alpha\eta/(1-\alpha)$.

From (3), (4), and (7), we have the signal-interference-noise-ratios (SINRs) of the best link $\mathsf{S} \longrightarrow \mathsf{R}$ and the link $\mathsf{R} \longrightarrow \mathsf{D}$ given in (8) and (9), respectively, [17][5] with notice that $\sigma_{\mathsf{R}}^2 \approx 0$ [18].

$$\gamma_{\mathsf{SR}} = \frac{P_{\mathsf{S}} \max\limits_{i=1,\ldots,N_{\mathsf{S}}} |h_{1,i}|^2}{\phi P_{\mathsf{S}} \max\limits_{i=1,\ldots,N_{\mathsf{S}}} |h_{1,i}|^2 |f|^2 + \sigma_{\mathsf{R}}^2} \approx \frac{1}{\phi |f|^2}. \tag{8}$$

$$\begin{aligned} \gamma_{\mathsf{RD}} =& \frac{P_{\mathsf{R}}}{\sigma_{\mathsf{D}}^2} \max_{j=1,\ldots,N_{\mathsf{D}}} |h_{2,j}|^2 \\ =& \frac{\phi P_{\mathsf{S}} \max\limits_{i=1,\ldots,N_{\mathsf{S}}} |h_{1,i}|^2 \max\limits_{j=1,\ldots,N_{\mathsf{D}}} |h_{2,j}|^2}{\sigma_{\mathsf{D}}^2}. \end{aligned} \tag{9}$$

From the aforementioned parameters and assumptions of the system model, we have the following Proposition 1.

Proposition 1. *The $\mathcal{OP}$ of MIMO-FDR system using the power transfer method TAS/SC is given by*

$$\mathcal{OP}_{SC} = 1 - \Psi(\Sigma)\Psi(x)\sqrt{\frac{4ij\gamma_{\mathsf{th}}\sigma_{\mathsf{D}}^2}{\phi P_{\mathsf{S}}\lambda_1\lambda_2}}\mathcal{K}_1\left(\sqrt{\frac{4ij\gamma_{\mathsf{th}}\sigma_{\mathsf{D}}^2}{\phi P_{\mathsf{S}}\lambda_1\lambda_2}}\right), \tag{10}$$

where

$$\Psi(\Sigma) = \sum_{i=1}^{N_{\mathsf{S}}} (-1)^{i-1}\binom{N_{\mathsf{S}}}{n} \sum_{j=1}^{N_{\mathsf{D}}} (-1)^{j-1}\binom{N_{\mathsf{D}}}{n},$$

$$\Psi\left(x\right) = 1 - \exp\left(-\frac{1}{\phi\lambda_3\gamma_{\mathsf{th}}}\right).$$

Proof. For the case of TAS/SC, let $X = \max_{i=1,\ldots,N_{\mathsf{S}}} |h_{1,i}|^2$ and $Y = \max_{j=1,\ldots,N_{\mathsf{D}}} |h_{2,j}|^2$, which are the products of random independent variables. Hence, the probability density functions (PDFs) of X and Y are respectively given by [19, 7-14]:

$$f_X(x) = \sum_{i=1}^{N_{\mathsf{S}}} (-1)^{i-1}\binom{N_{\mathsf{S}}}{i}\frac{i}{\lambda_1}\exp\left(-\frac{ix}{\lambda_1}\right). \tag{11}$$

$$f_Y(y) = \sum_{j=1}^{N_{\mathsf{D}}} (-1)^{j-1}\binom{N_{\mathsf{D}}}{j}\frac{j}{\lambda_2}\exp\left(-\frac{jy}{\lambda_2}\right), \tag{12}$$

where $\binom{n}{k} = \frac{n!}{k!(n-k)!}$.

Based on the proposed DF protocol and from (8), (9), the end-to-end SINR, γ_{e2e}, can be rewritten as [20]

$$\gamma_{\mathsf{e2e}} = \min\left(\frac{1}{\phi|f|^2}, \frac{\phi P_{\mathsf{S}} XY}{\sigma_{\mathsf{D}}^2}\right). \tag{13}$$

From (13), let $\mathcal{Z} = XY$, $\mathcal{W} = |f|^2$. The joint cumulative distribution function (CDF) of two random variables (X, Y) is

$$\begin{aligned} F_{\mathcal{Z}}\left(z\right) =& \Pr\left(XY < z\right) \\ =& \int_0^\infty F_X\left(\frac{z}{y}\right) f_Y\left(y\right) dy. \end{aligned} \tag{14}$$

For the Rayleigh fading channel, it is assumed that the weight of all branches all are the same and independent. Hence, the CDF of $\mathcal{Z}$ is given by

$$F_{\mathcal{Z}}\left(z\right) = \int_0^\infty \left[1 - \exp\left(-\frac{z}{y\lambda_1}\right)\right]^{N_{\mathsf{S}}} f_Y\left(y\right) dy. \tag{15}$$

By applying the binomial expansion [21, (1.111)] and substituting (11) and (12) into (15), we obtain

$$F_{\mathcal{Z}}\left(z\right) = 1 - \Psi\left(\Sigma,\, N_{\mathsf{S}}, N_{\mathsf{D}}\right)\frac{j}{\lambda_2}\int_0^\infty \exp\left(-\frac{iz}{y\lambda_1} - \frac{jy}{\lambda_2}\right) dy. \tag{16}$$

Using [21, (3.324.1)], we have

$$F_{\mathcal{Z}}\left(z\right) = 1 - \Psi\left(\Sigma,\, N_{\mathsf{S}}, N_{\mathsf{D}}\right)\sqrt{\frac{4ijz}{\lambda_1\lambda_2}}\mathcal{K}_1\left(\sqrt{\frac{4ijz}{\lambda_1\lambda_2}}\right), \tag{17}$$

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[5] It should be noted from (8) and (9) that γ_{SR} and γ_{RD} are independent. Hence analysis approach of using the independence of SNRs of the multi hops we have CDF of the γ_{e2e}.

where

$$\Psi\left(\Sigma,\, N_{\mathsf{S}}, N_{\mathsf{D}}\right) = \sum_{i=1}^{N_{\mathsf{S}}} (-1)^{i-1} \binom{N_{\mathsf{S}}}{i} \sum_{j=1}^{N_{\mathsf{D}}} (-1)^{j-1} \binom{N_{\mathsf{D}}}{j}.$$

Based on the definition of $\mathcal{OP}$ of the proposed system [7], we can rewrite the expression of $\mathcal{OP}$ as

$$\begin{aligned}\mathcal{OP} =& \Pr\left[(1-\alpha)\log_2\left(1+\gamma_{\mathsf{e2e}}\right) < \mathcal{R}\right] \\ =& \Pr\left[\min\left(\frac{1}{\phi\mathcal{W}}, \frac{\phi P_{\mathsf{S}}\mathcal{Z}}{\sigma_{\mathsf{D}}^2}\right) < \gamma_{\mathsf{th}}\right] \\ =& 1-\Pr\left[\frac{1}{\phi\mathcal{W}} > \gamma_{\mathsf{th}},\;\; \frac{\phi P_{\mathsf{S}}\mathcal{Z}}{\sigma_{\mathsf{D}}^2} > \gamma_{\mathsf{th}}\right], \end{aligned} \tag{18}$$

where $\gamma_{\mathsf{th}} = 2^{\mathcal{R}/(1-\alpha)} - 1$ denotes the SNR threshold at D so that the information from S can be decoded correctly at the target rate of $\mathcal{R}$. The exponent $(1-\alpha)$ is due to the two consecutive time slots for communication between source and destination.

It should be noted that $\mathcal{W}$ and $\mathcal{Z}$ in (18) are independent RVs. Thus, we can be rewrite the expression of $\mathcal{OP}$ as

$$\begin{aligned}\mathcal{OP} =& 1-\Pr\left(\mathcal{W} < \frac{1}{\gamma_{th}\phi}\right)\Pr\left(\mathcal{Z} > \frac{\gamma_{\mathsf{th}}\sigma_{\mathsf{D}}^2}{\phi P_{\mathsf{S}}}\right) \\ =& 1-\left[1-\exp\left(-\frac{1}{\gamma_{\mathsf{th}}\phi\lambda_3}\right)\right]\left[1-F_{\mathcal{Z}}\left(\frac{\gamma_{\mathsf{th}}\sigma_{\mathsf{D}}^2}{\phi P_{\mathsf{S}}}\right)\right]. \end{aligned} \tag{19}$$

Finally, by substituting (17) into (19), we obtain the expression of $\mathcal{OP}$ as in (10). ■

B. The TAS/MRC scheme

The mathematical expression of the $\mathcal{OP}$ of TAS/MRC scheme is given in the Proposition 2.

Proposition 2. *The $\mathcal{OP}$ of FDR-MIMO system using the power transfer method TAS/MRC is given by*

$$\begin{aligned}\mathcal{OP}_{MRC} = 1-&\left[1-\exp\left(-\frac{1}{\phi\lambda_3\gamma_{\mathsf{th}}}\right)\right]\sum_{i=1}^{N_{\mathsf{S}}}(-1)^{i-1}\binom{N_{\mathsf{S}}}{i} \\ &\times\frac{2}{\Gamma\left(N_{\mathsf{D}}\right)\lambda_2^{N_{\mathsf{D}}}}\left(\frac{i\gamma_{\mathsf{th}}\sigma_{\mathsf{D}}^2\lambda_2}{\phi P_{\mathsf{S}}\lambda_1}\right)^{\frac{N_{\mathsf{D}}}{2}} \\ &\times\mathcal{K}_{N_{\mathsf{D}}}\left(2\sqrt{\frac{i\gamma_{\mathsf{th}}\sigma_{\mathsf{D}}^2}{\lambda_1\lambda_2\phi P_{\mathsf{S}}}}\right). \end{aligned} \tag{20}$$

Proof. Assuming that MRC technical is used at D, the γ_{SR} is given as in (8) and the γ_{RD} is

$$\begin{aligned}\gamma_{\mathsf{RD}} =& \frac{P_{\mathsf{R}}}{\sigma_{\mathsf{D}}^2}\sum\nolimits_{j=1}^{N_{\mathsf{D}}}\left|h_{2,j}\right|^2 \\ =& \frac{\phi P_{\mathsf{S}}\max\limits_{i=1,\ldots,N_{\mathsf{S}}}\left|h_{1,i}\right|^2}{\sigma_{\mathsf{D}}^2}\sum\nolimits_{j=1}^{N_{\mathsf{D}}}\left|h_{2,j}\right|^2. \end{aligned} \tag{21}$$

For the case of using MRC technique at D, we let $X = \max_{i=1,\ldots,N_{\mathsf{S}}}\left|h_{1,i}\right|^2$, $Y = \sum_{j=1}^{N_{\mathsf{D}}}\left|h_{2,j}\right|^2$. Therefore, the PDF and CDF of Y are respectively expressed as [22]

$$F_Y\left(y\right) = 1 - e^{-\frac{y}{\lambda_2}}\sum_{j=0}^{N_{\mathsf{D}}-1}\frac{1}{j!}\left(\frac{y}{\lambda_2}\right)^j. \tag{22}$$

$$f_Y(y) = \frac{y^{N_{\mathsf{D}}-1}e^{-\frac{y}{\lambda_2}}}{\Gamma\left(N_{\mathsf{D}}\right)\lambda_2^{N_{\mathsf{D}}}}. \tag{23}$$

The PDF of X is given in (11). Similar to (14) in Section III-A, we have the CDF of $\mathcal{Z}$ as

$$\begin{aligned}F_{\mathcal{Z}}(z) =& \Pr(XY < z) \\ =& 1-\mathcal{A}_{\mathcal{X}}\left(\Sigma, N_{\mathsf{S}}, N_{\mathsf{D}}\right)\int_0^\infty y^{N_{\mathsf{D}}-1}\exp\left(-\frac{iz}{y\lambda_1}-\frac{y}{\lambda_2}\right)dy, \end{aligned} \tag{24}$$

From [21, (3.471.9)], (24) can be rewritten as

$$F_{\mathcal{Z}}(z) = 1-2\mathcal{A}_{\mathcal{X}}\left(\Sigma, N_{\mathsf{S}}, N_{\mathsf{D}}\right)\left(\frac{iz\lambda_2}{\lambda_1}\right)^{\frac{N_{\mathsf{D}}}{2}}\mathcal{K}_{N_{\mathsf{D}}}\left(2\sqrt{\frac{iz}{\lambda_1\lambda_2}}\right). \tag{25}$$

where

$$\mathcal{A}_{\mathcal{X}}\left(\Sigma, N_{\mathsf{S}}, N_{\mathsf{D}}\right) = \sum_{i=1}^{N_{\mathsf{S}}}(-1)^{i-1}\binom{N_{\mathsf{S}}}{i}\frac{1}{\Gamma\left(N_{\mathsf{D}}\right)\lambda_2^{N_{\mathsf{D}}}}.$$

Finally, using (18) and substituting (25) into (19), the $\mathcal{OP}$ expression of MRC technique at the D is given as (20). ■

C. The MRT/MRC scheme

In this section, we derive the exact expression of $\mathcal{OP}$ in a scenario where beamforming is used at S to transmit signals to R. When MRT scheme is used, the amount of energy harvested at R is the summation of the amount of energy at each branch, that is

$$E_h^{\mathrm{MRT}} = \alpha T\eta P_{\mathsf{S}}\sum_{i=1}^{N_{\mathsf{S}}}\left|h_{1,i}\right|^2. \tag{26}$$

Consequently, the transmit power at R is calculated as

$$P_{\mathsf{R}} = \frac{E_h^{\mathrm{MRT}}}{1-\alpha} = \phi P_{\mathsf{S}}\sum_{i=1}^{N_{\mathsf{S}}}\left|h_{1,i}\right|^2. \tag{27}$$

The outage probability of the system with DF protocol is given in the following Proposition 3.

Proposition 3. *The $\mathcal{OP}$ of FDR- MIMO system using the power transfer scheme MRT S and MRC scheme at D is given by*

$$\begin{aligned}\mathcal{OP}_{MRT} = 1-&\left[1-\exp\left(\frac{-1}{\phi\lambda_3\gamma_{\mathsf{th}}}\right)\right]\sum_{i=0}^{N_{\mathsf{S}}-1}\frac{1}{i!}\left(\frac{\gamma_{\mathsf{th}}\sigma_{\mathsf{D}}^2}{\lambda_1\phi P_{\mathsf{S}}}\right)^i \\ &\times\frac{2}{\Gamma\left(N_{\mathsf{D}}\right)\lambda_2^{N_{\mathsf{D}}}}\left(\frac{\gamma_{\mathsf{th}}\lambda_1}{\phi P_{\mathsf{S}}\lambda_2}\right)^{\frac{N_{\mathsf{D}}-i}{2}} \\ &\times\mathcal{K}_{N_{\mathsf{D}}-i}\left(2\sqrt{\frac{\gamma_{\mathsf{th}}}{\phi P_{\mathsf{S}}\lambda_1\lambda_2}}\right). \end{aligned} \tag{28}$$

Proof. In other to obtain $\mathcal{OP}$ as in (28) we consider the CDFs of $X = \sum_{i=1}^{N_\mathsf{S}} |h_{1,i}|^2$and $Y = \sum_{j=1}^{N_\mathsf{D}} |h_{2,j}|^2$. Since the MRT and MRC schemes are used, X and Y are chi-squared distribution. They are determined by the summation of i.i.d exponential random variables N_S and N_D. We have the CDF of X as

$$F_X(x) = 1 - e^{-\frac{x}{\lambda_1}} \sum_{i=0}^{N_\mathsf{S}-1} \frac{1}{i!}\left(\frac{x}{\lambda_1}\right)^i. \tag{29}$$

We should be reminded that the CDF of Y is presented in (22).

After some manipulations, we obtain

$$\begin{aligned} F_\mathcal{Z}(z) =& \mathbb{E}_Y\left\{1 - e^{-\frac{z}{\lambda_1 Y}} \sum_{i=0}^{N_\mathsf{S}-1} \frac{1}{i!}\left(\frac{z}{Y\lambda_1}\right)^i\right\} \\ =& 1 - \int_0^\infty e^{-\frac{z}{\lambda_1 y}} \sum_{i=0}^{N_\mathsf{S}-1} \frac{1}{i!}\left(\frac{z}{y\lambda_1}\right)^i f_Y(y)dy. \end{aligned} \tag{30}$$

By substituting (23) into (30) and using [21, (3.471.9)], we have

$$\begin{aligned} F_\mathcal{Z}(z) = 1 - & \sum_{i=0}^{N_\mathsf{S}-1} \frac{1}{i!}\left(\frac{z}{\lambda_1}\right)^i \frac{2}{\Gamma(N_\mathsf{D})\lambda_2^{N_\mathsf{D}}} \left(\frac{\lambda_1}{z\lambda_2}\right)^{\frac{N_\mathsf{D}-i}{2}} \\ & \times \mathcal{K}_{N_\mathsf{D}-i}\left(2\sqrt{\frac{z}{\lambda_1\lambda_2}}\right). \end{aligned} \tag{31}$$

Finally, replacing (31) into (18), we obtain the expression of $\mathcal{OP}$ as in (28). ■

IV. Simulation Results

In this section, we verify our analysis by comparing the theoretical results with the Monte-Carlo simulation results. We also study the effect of the number of antennas at source node and destination node on the outage probability three schemes, i.e., TAS/SC, TAS/MRC, and MRT/MRC, in the proposed system. The system settings are as follows. The source transmission rate $\mathcal{R}_\mathsf{th} = 1$. The energy harvesting efficiency is $\eta = 1$. For the channel settings, we adopt a simplified path loss model, i.e., $\lambda_k = d_{ki}^{-m}$, where d_{ki} and m denote the distance of hop k and the path loss exponent, respectively. For illustrative purpose, we set $\lambda_{1i} = \lambda_{2j} = 1$, $(i = 1, \ldots, N_\mathsf{S}, j = 1, \ldots, N_\mathsf{D})$. Fig. 2 plots the $\mathcal{OP}$ versus average power transmission of the source for three scenarios, i.e., (TAS/SC, TAS/MRC, and MRT/MRC). We can see that among three considered schemes (TAS/SC, TAS/MRC, and MRT/MRC), MRT/MRC is the best one, which provides the highest outage performance. It is because that the diversity gain of MRT scheme is better than that of TAS scheme. Moreover, from (6) and (26) , we can see that the amount of harvested energy of MRT scheme is more than TAS scheme. We also see that the analysis results are in excellent agreement with the simulation ones, confirming the correctness of our mathematical analysis. The effect of the number of antennas on the outage performance is shown in Fig. 3. We consider three following scenarios $[N_\mathsf{S}\ \ N_\mathsf{D}] = [1\ \ 1]$, $[N_\mathsf{S}\ \ N_\mathsf{D}] = [1\ \ 2]$, and $[N_\mathsf{S}\ \ N_\mathsf{D}] = [2\ \ 2]$. As observed from Fig. 3, when the number of antennas increases, the outage probability performance of the network is improved. Obviously, we can see from Fig. 3 that the slopes of $\mathcal{OP}$ curves representing the diversity order of the system depends on the number of antennas of both source node and destination node. Generally, the diversity order of the system is $\min(N_\mathsf{S}, N_\mathsf{D})$.

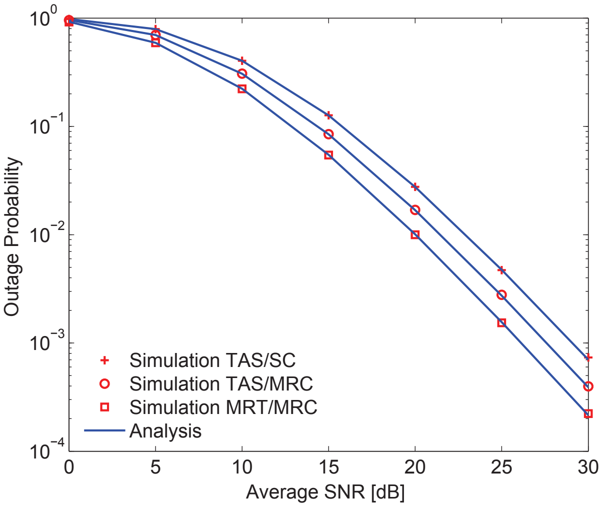

Fig. 2. Outage probability versus average SNR, $\alpha = 0.3$, $N_\mathsf{S} = N_\mathsf{D} = 2$.

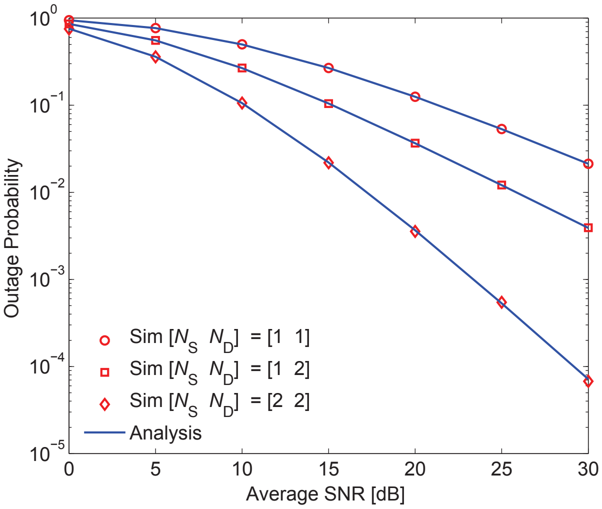

Fig. 3. Outage probability versus the transmitted power from source for different values of the number of antennas, with $\alpha = 0.3$ and TAS/MRC scheme.

In Fig. 4, we evaluate the $\mathcal{OP}$ versus TS protocol. As shown in Fig. 4, there are three different scenarios, i.e. $[N_\mathsf{S}\ \ N_\mathsf{D}] = [1\ \ 1]$, $[N_\mathsf{S}\ \ N_\mathsf{D}] = [1\ \ 2]$ and $[N_\mathsf{S}\ \ N_\mathsf{D}] = [2\ \ 2]$. We can see that there exists a unique optimal value of α to minimize $\mathcal{OP}$. In addition, for different antenna settings, the optimal α is not the same. When a number of antennas is increases, the value of α potentially reduces. We also see that the analysis results are in

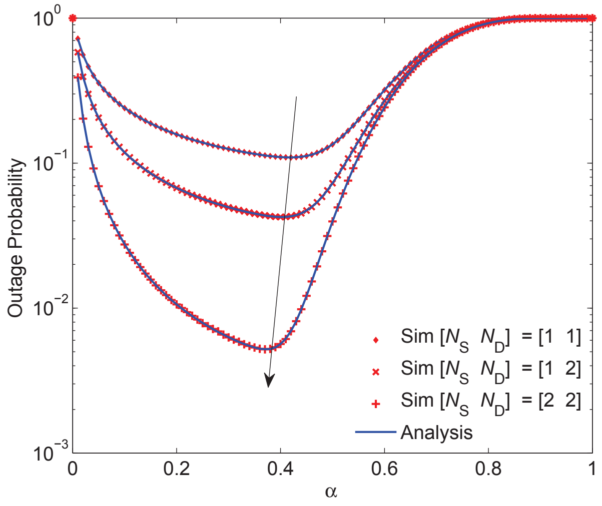

Fig. 4. Effect of α on outage probability for the TAS/SC schemes, with $\mathrm{EbN0} = 20$ dB.

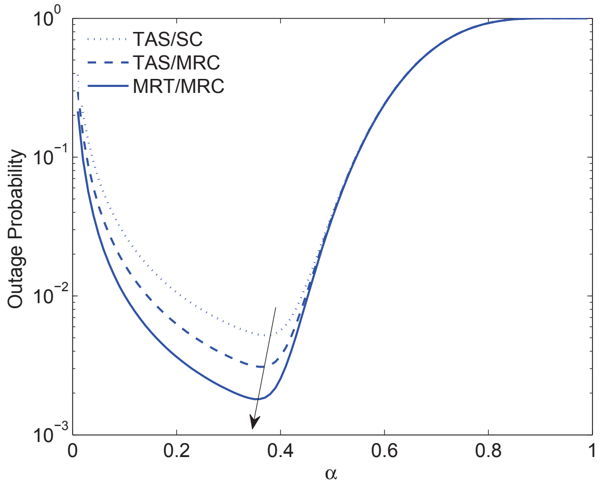

Fig. 5. Effect of α on outage probability for three different schemes, with $\mathrm{EbN0} = 20$ dB.

excellent agreement with the simulation ones confirming the correctness of the proposed analysis approach.

Fig. 5 depicts the impact of optimal time switching α on the $\mathcal{OP}$ for three schemes of operation. Similar to Fig. 4, we can observe that there exists a unique optimal value of α to minimize $\mathcal{OP}$. Each scheme has different optimal value of α. We can see that the gap of these three schemes is the same for the case of fixed transmission power and $[N_\mathrm{S}\ N_\mathrm{D}] = [2\ 2]$.

V. CONCLUSIONS

In this paper, we have studied the $\mathcal{OP}$ of FD relaying in the RF energy harvesting system. We evaluate three schemes of system based on the outage probability, i.e., TAS/SC, TAS/MRC, and MRT/MRC. Moreover, we derive the closed-form expression of $\mathcal{OP}$ of the system over Rayleigh fading channel. The numerical results obtained in this paper show that multiple antennas equipped at both S and D can significantly improve the system performance.

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