Wireless Powered Dual-Hop Multiple Antenna Relay Transmission in the Presence of Interference

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Abstract— **This paper investigates the impact of the multiple antenna and co-channel interference (CCI) on the outage performance of a dual-hop amplify-and-forward energy harvesting relaying network. The energy constrained relay is powered by radio frequency signals and employs the power splitting receiver architecture. To exploit the benefit of multiple antennas, two different linear processing schemes are investigated, namely, Maximum ratio combining/maximal ratio transmission (MRC/MRT) and Minimum mean-square error/MRT (MMSE/MRT). For both schemes, a new closed-form outage lower bound and a simple high signal-to-noise ratio outage approximation are derived, respectively. Also, the achievable diversity order is quantified. In addition, we study the optimal power splitting ratio which minimizes the outage probability. Our results show that, by increasing the energy harvesting capability, the implementation of multiple antennas significantly improves the systems performance. Moreover, CCI could be potentially exploited to boost the performance, while how much performance gain can be obtained depends on the choice of the linear processing scheme.**

I. Introduction

With the rapid proliferation of low-cost wireless devices such as sensors, how to prolong the lifetime of these energy constrained devices has become a critical problem to be addressed. In this context, energy harvesting techniques, which harvest energy from external natural resources, such as solar power, wind energy or thermoelectric effects have gained significant interest in recent years [1–5]. However, due to the randomness and intermittent nature of external resources, guaranteeing reliable supply of power is challenging. Responding to this, wireless energy transfer technique, which can much reliably collect energy from ambient radio frequency (RF) signals [6], has emerged as a promising alternative [7].

Cooperative relaying networks constitute an important application of RF energy harvesting, where an energy-constrained relay with limited battery reserves relies on some external charging mechanism to assist the transmission of source information to the destination [1]. As such, a number of works have exploited the idea of achieving simultaneous information and energy transfer in cooperative relay networks [7–10]. Specifically, [8] studied the throughput performance of an amplify-and-forward (AF) relaying system for both time-switching and power-splitting protocols and [9] considered the power allocation strategies for decode-and-forward relaying system with multiple source-destination pairs. More recently, the performance of energy harvesting cooperative networks with randomly distributed users was studied in [7, 10]. However, all these works are limited to the single antenna setup and all assume an interference free environment, hence the effect of multiple antenna and interference remains unknown.

Motivated by this, we consider a dual-hop AF relaying system where the source and destination are equipped with a single antenna while the relay is equipped with multiple antennas. The energy constrained relay collects energy from ambient RF signals and uses the harvested energy to forward the information to the destination. We assume that the signal at the relay is corrupted by co-channel interference (CCI). Unlike the conventional wireless systems, where CCI has always been regarded as a harmful factor, in the energy harvesting context, CCI is actually a double edged sword. Although it corrupts the desired signal, it also provides additional energy [11]. Hence, it could be potentially exploited to improve the system performance. As such, linear processing schemes are proposed to extract the possible benefit of CCI. Specifically, two different schemes, i.e., Maximum ratio combining/maximal ratio transmission (MRC/MRT) [12] and Minimum mean-square error/MRT (MMSE/MRT) are investigated.

The main contributions of the paper include tight closed-form outage lower bounds for both linear processing schemes, as well as simple outage probability expressions valid in the high signal-to-noise (SNR) region, which not only enables the characterization of the key performance measures such as the achievable diversity order and coding gain, but also allows for fast evaluation of the impact of various key system parameters on the outage performance. In addition, the optimal power splitting ratio minimizing the outage probability is studied. Our results demonstrate that the implementation of multiple antennas can significantly improve the systems performance by increasing the energy harvesting capability and providing

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additional diversity gain. Furthermore, It is illustrated that the CCI could be potentially exploited to significantly enhance the systems performance. However, the choice of linear processing schemes plays a critical role in determining how much gain could be extracted from CCI.

II. System Model

We consider a dual-hop multiple antenna AF energy harvesting relaying system as shown in Fig. 1(a), where both the source and the destination are equipped with a single antenna, while the relay is equipped with N antennas Typically, the energy harvested from a single antenna is not sufficient for reliable device operation [13], hence we employ the same multiple antennas relay model as [7] to enhance the RF power harvesting. The source sends information to the destination through an energy constrained relay. We now adopt the following assumptions: 1) The direct link between the source and the destination does not exist due to obstacles and/or severe fading. 2) The channel remains constant over the block time T and varies independently and identically from one block to the other, and has a Rayleigh distributed magnitude. 3) As in [14–16], full CSI is assumed to be available at the relay.

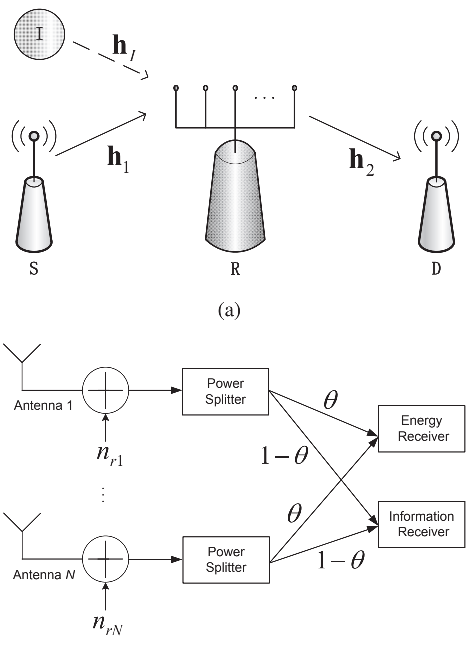


Fig. 1. (a) System model: S, R and D denote the source, relay and destination node, respectively. (b) Block diagram of the relay receiver with the power splitting protocol.

We adopt the power splitting protocol as in [17]. Specifically, the entire communication consists of two time slots with duration of $\frac{T}{2}$ each. At the end of the first phase, each antenna at the relay node splits the received source signal into two streams, one for energy harvesting and the other for information processing as shown in Fig. 1(b). We consider the pessimistic case where power splitting only reduces the signal power, but not the noise [9, 18]. Hence, our results provide a lower bound on the performance for practical systems.

We assume that the relay is subject to a single dominant interferer and additive white Gaussian noise (AWGN) while the destination is corrupted by the AWGN only. It is worth pointing out that the single dominant interferer assumption has been widely adopt in the literature [19, 20]. Moreover, such a system model enables us to gain key insights on the joint effect of CCI and multiple antennas on the performance.

Let θ denote the power splitting ratio,[1] then the signal at the input of the information receiver at the relay is given by

$$\mathbf{y}_r = \sqrt{(1-\theta)P_s/d_1^\tau}\mathbf{h}_1 x + \sqrt{(1-\theta)P_I/d_I^\tau}\mathbf{h}_I s_I + \mathbf{n}_r,$$

where P_s denotes the source power. $\mathbf{h}_1$ is an $N \times 1$ vector with entries following identically and independently distributed (i.i.d.) $\mathcal{CN}(0,1)$, where $\mathcal{CN}(0,1)$ denotes a scalar complex Gaussian distribution with zero mean and unit variance. d_1 denotes the distance between the source and the relay. τ is the path loss exponent. x is the source message with unit power. P_I is the interference power, d_I denotes the distance between the interferer and the relay and s_I is the interference symbol with unit power. $\mathbf{h}_I$ is an $N \times 1$ vector with entries following i.i.d. $\mathcal{CN}(0,1)$. $\mathbf{n}_r$ is an $N \times 1$ vector and denotes the AWGN with $\mathtt{E}\{\mathbf{n}_r\mathbf{n}_r^\dagger\} = N_0\mathbf{I}$, where $\mathtt{E}$ is the expectation operation and $(\cdot)^\dagger$ is the transpose and conjugate operation.

According to [11], at the end of the first phase, the overall energy harvested during half of the block time $\frac{T}{2}$ is given by

$$E_h = \eta\theta\left(\frac{P_s}{d_1^\tau}\|\mathbf{h}_1\|_F^2 + \frac{P_I}{d_I^\tau}\|\mathbf{h}_I\|_F^2\right)\frac{T}{2}, \tag{1}$$

where $0 < \eta < 1$ denotes the energy harvesting efficiency factor and $\|\mathbf{h}\|_F$ denotes the Frobenius norm.

During the second phase, the relay transmits a transformed version of the received signal to the destination using the harvested power. Hence, the signal at the destination can be expressed as

$$y_d = \sqrt{1/d_2^\tau}\mathbf{h}_2\mathbf{W}\mathbf{y}_r + n_d, \tag{2}$$

where $\mathbf{h}_2$ is a $1 \times N$ vector and denotes the relay-destination channel, and its entries follow i.i.d. $\mathcal{CN}(0,1)$. d_2 denotes the distance between the relay and the destination. n_d is the AWGN at the destination with $\mathtt{E}\{n_d^* n_d\} = N_0$, where $*$ denotes the conjugate operator. $\mathbf{W}$ is the transformation matrix applied at the information receiver at the relay with $\mathtt{E}\{\|\mathbf{W}\mathbf{y}_r\|_F^2\} = P_r$, where $P_r = \frac{E_h}{T/2}$. Obviously, the performance of the system depends on the choice of $\mathbf{W}$. However the optimal relay processing matrix $\mathbf{W}$ maximizing the end-to-end signal-to-interference-and-noise ratio (SINR) of the system does not seem to be analytically tractable due to the non-convex nature of the problem. Hence, in the following, we consider three heuristic two-stage relay processing strategies proposed in [21], i.e., the matrix $\mathbf{W}$ admits the rank-1 structure $\mathbf{W} = \omega\frac{\mathbf{h}_2^\dagger}{\|\mathbf{h}_2\|_F}\mathbf{w}_1$, where $\mathbf{w}_1$ is a $1 \times N$ linear combining vector, which depends on the linear combining scheme employed by the relay and will be specified in the ensuing sections.

III. Performance Analysis

A. MRC/MRT Scheme

For the MRC/MRT scheme, $\mathbf{w}_1$ is set to match the first hop channel, hence, $\mathbf{w}_1 = \mathbf{h}_1^\dagger \big/ \|\mathbf{h}_1\|_F$. Therefore, the end-to-end

[1]The optimality of uniform θ can be established by using similar methods as in [18]

SINR of the MRC/MRT scheme can be expressed as

$$\gamma_I^{\mathsf{MRC}} = \frac{\gamma_{I1}^{\mathsf{MRC}}\gamma_{I2}^{\mathsf{MRC}}}{\gamma_{I1}^{\mathsf{MRC}} + \gamma_{I2}^{\mathsf{MRC}} + 1}, \tag{3}$$

where $\gamma_{I1}^{\mathsf{MRC}} = \frac{(1-\theta)\rho_1}{d_1^\tau}\|\mathbf{h}_1\|_F^2 \Big/ \left(\frac{(1-\theta)\rho_I}{d_I^\tau}\frac{|\mathbf{h}_1^\dagger \mathbf{h}_I|^2}{\|\mathbf{h}_1\|_F^2} + 1\right)$, $\gamma_{I2}^{\mathsf{MRC}} = \frac{\eta\theta}{d_2^\tau}\left(\frac{\rho_1}{d_1^\tau}\|\mathbf{h}_1\|_F^2 + \frac{\rho_I}{d_I^\tau}\|\mathbf{h}_I\|_F^2\right)\|\mathbf{h}_2\|_F^2$, $\rho_1 = P_s/N_0$ and $\rho_I = P_I/N_0$.

1) Outage Probability: Since the exact analysis appears to be difficult, in the following we focus on deriving an outage lower bound and a simple high SNR outage approximation. Noticing that the end-to-end SINR in (3) can be tightly upper bounded by

$$\gamma_I^{\mathsf{MRC}} \le \gamma_I^{\mathsf{up}} = \min\left(\gamma_{I1}^{\mathsf{MRC}}, \gamma_{I2}^{\mathsf{MRC}}\right), \tag{4}$$

and the outage probability of the MRC/MRT scheme is lower bounded by $P_{I\mathsf{out}}^{\mathsf{LMRC}} = \mathrm{Prob}\left(\gamma_I^{\mathsf{up}} < \gamma_{\mathsf{th}}\right)$. Then we have the following key result:

Theorem 1: If $\rho_1 \neq \rho_I$,[2] the outage probability of the MRC/MRT scheme can be lower bounded as

$$P_{I\mathsf{out}}^{\mathsf{LMRC}} = 1 - F_1^{\mathsf{MRC}} F_2^{\mathsf{MRC}}, \tag{5}$$

where

$$F_1^{\mathsf{MRC}} = \frac{d_I^\tau e^{-\frac{d_1^\tau \gamma_{\mathsf{th}}}{(1-\theta)\rho_1}}}{(1-\theta)\rho_I}\sum_{m=0}^{N-1}\left(\frac{d_1^\tau\gamma_{\mathsf{th}}}{(1-\theta)\rho_1}\right)^m \times \sum_{n=0}^{m}\frac{1}{(m-n)!}\left(\frac{(1-\theta)\rho_1\rho_I}{d_I^\tau\rho_1 + d_1^\tau\rho_I\gamma_{\mathsf{th}}}\right)^{n+1}, \tag{6}$$

and F_2^{MRC} can be expressed as in (7) shown on the top of the next page, where $K_v(x)$ is the v-th order modified Bessel function of the second kind [22, Eq. (8.407.1)].

Proof: Due to space limitation, the proof is omitted. □

While Theorem 1 is useful for the evaluation of the system's outage probability, the expression is too complex to yield much useful insights. Motivated by this, we now look into the high SNR region, and derive a simple approximation for the outage probability, which enables the characterization of the achievable diversity order of the system.

Theorem 2: In the high SNR region, i.e., $\rho_1 \to \infty$, outage probability of the MRC/MRT scheme can be approximated as[3]

$$P_{I\mathsf{out}}^{\mathsf{MRC}} \approx \left(\frac{d_1^\tau\gamma_{\mathsf{th}}}{\rho_1}\right)^N \left(\frac{\sum\limits_{n=0}^{N}\frac{((1-\theta)\rho_I)^n}{d_I^{n\tau}(N-n)!}}{(1-\theta)^N} + d_2^{N\tau} \times \frac{\sum\limits_{i=0}^{N-1}\binom{N-1}{i}(-1)^{N-i-1}\frac{{}_2F_1\left(N,2N-i-1;2N-i;1-\frac{d_1^\tau\rho_I}{d_I^\tau\rho_1}\right)}{2N-i-1}}{(\eta\theta)^N\Gamma(N+1)\Gamma(N)}\right), \tag{8}$$

where $\Gamma(x)$ is the gamma function and ${}_2F_1(a,b;c;z)$ is the Gauss Hypergeometric Function [22, Eq. (9.100)].

Proof: Due to space limitation, the proof is omitted. □

For the special case where the relay is equipped with a single antenna, i.e., $N = 1$, with the help of [22, Eq. (9.121.6)], (8) reduces to

$$P_{I\mathsf{out}}^{\mathsf{MRC}} \approx \left(\frac{1}{1-\theta} + \frac{\rho_I}{d_I^\tau} + \frac{d_2^\tau\left(\ln\frac{\rho_1}{d_1^\tau} - \ln\frac{\rho_I}{d_I^\tau}\right)}{\eta\theta}\right)\frac{d_1^\tau\gamma_{\mathsf{th}}}{\rho_1}. \tag{9}$$

Theorem 2 indicates that a full diversity order of N is achievable in the presence of CCI for the MRC/MRT scheme. Moreover, from (9), we see that the effect of CCI could be either beneficial or detrimental, depending on the relationship between ρ_I, d_I^τ, d_2^τ η and θ, i.e., when $\frac{\rho_I}{d_I^\tau} - \frac{d_2^\tau(\ln\rho_I - \ln d_I^\tau)}{\eta\theta}$ is positive, CCI is detrimental, while when $\frac{\rho_I}{d_I^\tau} - \frac{d_2^\tau(\ln\rho_I - \ln d_I^\tau)}{\eta\theta}$ is negative, CCI is beneficial. This suggests that, in energy harvesting relaying systems, CCI could be potentially exploited to improve the performance.

2) Optimal θ Analysis in the High SNR Region: The right selection of the power splitting ratio θ is crucial for the system's performance. A high value of θ could provide more transmission power at the relay, which benefits the relay-destination transmission. Nevertheless, a large θ also deteriorates the quality of the source-relay transmission. Hence, there exists a tradeoff. For tractability, we focus on the outage performance in the high SNR region.

Starting from the high SNR approximation of P_{out} in (8), the optimal θ, which is the solution of the optimization problem $\min\limits_{0<\theta<1} P_{\mathsf{out}}$, can be obtained by solving the equivalent problem in (10) shown on the top of the next page.

Proposition 1: The optimal θ is a root of the following polynomial

$$\sum_{n=0}^{N-1}\mathcal{A}(n)(1-\theta)^{n-N-1} - \frac{\mathcal{B}}{\theta^{N+1}} = 0, \tag{11}$$

where $0 < \theta < 1$, $\mathcal{A}(n) = \frac{\rho_I^n}{d_I^{n\tau}(N-n-1)!}$ and $\mathcal{B} = \frac{d_2^{N\tau}}{\eta^N\Gamma^2(N)}\sum\limits_{i=0}^{N-1}\binom{N-1}{i}(-1)^{N-i-1}\frac{{}_2F_1\left(N,2N-i-1;2N-i;1-\frac{\rho_I d_1^\tau}{\rho_1 d_I^\tau}\right)}{2N-i-1}$.

Proof: It is easily to prove that, when $\rho_1 \to \infty$, there is only one root (denoted by θ^*) on the interval of $(0,1)$ for the equation $f'_{\mathsf{MRC}}(\theta) = 0$, and we can also note that $f'_{\mathsf{MRC}}(0) = -\infty$ and $f'_{\mathsf{MRC}}(1) = +\infty$. Due to the continuity of $f'_{\mathsf{MRC}}(\theta)$, we have $f'_{\mathsf{MRC}}(\theta) < 0, \theta \in (0,\theta^*)$ and $f'_{\mathsf{MRC}}(\theta) > 0$, $\theta \in (\theta^*, 1)$, which means that $f_{\mathsf{MRC}}(\theta)$ first decreases as θ from 0 to θ^* and then increases as θ from θ^* to 1. Therefore, the global minimum of $f_{\mathsf{MRC}}(\theta)$ can be obtained by solving $f'_{\mathsf{MRC}}(\theta) = 0$. □

For the special case $N = 1$, the optimal solution can be given in closed-form as follows:

$$\theta_{\mathsf{MRC}}^{\mathsf{opt}} = \frac{\sqrt{\frac{d_I^\tau\rho_1\left(\ln\rho_I - \ln\rho_1 - \ln d_I^\tau + \ln d_1^\tau\right)}{\eta\left(d_1^\tau\rho_I - d_I^\tau\rho_1\right)}}}{1 + \sqrt{\frac{d_I^\tau\rho_1\left(\ln\rho_I - \ln\rho_1 - \ln d_I^\tau + \ln d_1^\tau\right)}{\eta\left(d_1^\tau\rho_I - d_I^\tau\rho_1\right)}}}. \tag{12}$$

This simple expression is quite informative, and it can be observed that the optimal θ in (12) is a decreasing function of η and ρ_I, and an increasing function of ρ_1, which can be

[2] For mathematical tractability, we only provide the result for the general case where the signal from the source and the interference have different power, i.e., $\rho_1 \neq \rho_I$. But the result for the special case $\rho_1 = \rho_I$ is much more easier and can be obtained in a similar way.

[3] It is worth pointing out that the result in Theorem 2 holds for all cases whether the signal power and CCI power are equal or not.

$$F_2^{\mathsf{MRC}} = \frac{2d_1^{N\tau}d_I^{N\tau}}{\rho_1^N\rho_I^N}\sum_{s=1}^{N}\frac{\prod_{j=1}^{s-1}(1-N-j)}{(N-s)!\,(s-1)!}\left(\frac{d_I^\tau}{\rho_I}-\frac{d_1^\tau}{\rho_1}\right)^{1-N-s}\sum_{m=0}^{N-1}\frac{1}{m!}\left(\frac{d_2^\tau\gamma_{\mathsf{th}}}{\eta\theta}\right)^{N+1-s}\times \left(\frac{d_1^\tau d_2^\tau\gamma_{\mathsf{th}}}{\eta\theta\rho_1}\right)^{\frac{m+s-N-1}{2}}K_{m+s-N-1}\left(2\sqrt{\frac{d_1^\tau d_2^\tau\gamma_{\mathsf{th}}}{\eta\theta\rho_1}}\right)+\frac{2d_1^{N\tau}d_I^{N\tau}}{\rho_1^N\rho_I^N}\sum_{s=1}^{N}\frac{\prod_{j=1}^{s-1}(1-N-j)}{(N-s)!\,(s-1)!}\times \left(\frac{d_1^\tau}{\rho_1}-\frac{d_I^\tau}{\rho_I}\right)^{1-N-s}\sum_{m=0}^{N-1}\frac{1}{m!}\left(\frac{d_2^\tau\gamma_{\mathsf{th}}}{\eta\theta}\right)^{N+1-s}\left(\frac{d_2^\tau d_I^\tau\gamma_{\mathsf{th}}}{\eta\theta\rho_I}\right)^{\frac{m+s-N-1}{2}}K_{m+s-N-1}\left(2\sqrt{\frac{d_2^\tau d_I^\tau\gamma_{\mathsf{th}}}{\eta\theta\rho_I}}\right). \quad (7)$$

$$\min_{0<\theta<1} \; f_{\mathsf{MRC}}(\theta) = \frac{\sum_{n=0}^{N}\frac{((1-\theta)\rho_I)^n}{d_I^{n\tau}(N-n)!}}{(1-\theta)^N} + \frac{d_2^{N\tau}\sum_{i=0}^{N-1}\binom{N-1}{i}(-1)^{N-i-1}\frac{{}_2F_1\left(N,2N-i-1;2N-i;1-\frac{d_1^\tau\rho_I}{d_I^\tau\rho_1}\right)}{2N-i-1}}{(\eta\theta)^N\Gamma(N+1)\Gamma(N)}. \quad (10)$$

explained as follows:

- As η increases, more transmission power can be collected at the relay, hence the bottleneck of the system performance lies in the SINR of the signal at the input of the information receiver. As a result, we should choose a smaller θ to improve the first hop performance.
- A large ρ_I provides more energy, while at the same time reduces the SINR of the first hop transmission. Hence, a smaller θ should be chosen to compensate the loss of the SINR.
- For large ρ_1, in general the first hop transmission quality is quite good, hence, it is beneficial to have more energy at the relay, i.e., a larger θ is desirable.

B. MMSE/MRT Scheme

In the previous subsection, we have shown that CCI has the potential to boost the system performance even when the MRC/MRT scheme is employed. Therefore, it is interesting to study how much gain can be achieved when a more sophisticated linear combining technique is utilized. As such, in this subsection, we focus on the MMSE/MRT scheme since it provides a fine balance between interference suppression and noise enhancement. According to [21], $\mathbf{w}_1$ is given by

$$\mathbf{w}_1 = \mathbf{h}_1^\dagger\left(\mathbf{h}_1\mathbf{h}_1^\dagger+\mathbf{h}_I\mathbf{h}_I^\dagger+\frac{d_I^\tau}{(1-\theta)\rho_I}\mathbf{I}\right)^{-1}. \quad (13)$$

Therefore, the end-to-end SINR of the MMSE/MRT scheme can be expressed as

$$\gamma_I^{\mathsf{MMSE}} = \frac{\gamma_{I1}^{\mathsf{MMSE}}\gamma_{I2}^{\mathsf{MMSE}}}{\gamma_{I1}^{\mathsf{MMSE}}+\gamma_{I2}^{\mathsf{MMSE}}+1}, \quad (14)$$

where $\gamma_{I1}^{\mathsf{MMSE}} = \frac{d_I^\tau\rho_1}{d_1^\tau\rho_I}\mathbf{h}_1^\dagger\mathbf{R}^{-1}\mathbf{h}_1$, $\mathbf{R} = \mathbf{h}_I\mathbf{h}_I^\dagger + \frac{d_I^\tau}{(1-\theta)\rho_I}\mathbf{I}$ and $\gamma_{I2}^{\mathsf{MMSE}} = \frac{\eta\theta}{d_2^\tau}\left(\frac{\rho_1}{d_1^\tau}\|\mathbf{h}_1\|_F^2+\frac{\rho_I}{d_I^\tau}\|\mathbf{h}_I\|_F^2\right)\|\mathbf{h}_2\|_F^2$.

1) Outage Probability:

Theorem 3: If $\rho_1 \neq \rho_I$, the outage probability of the MMSE/MRT scheme can be lower bounded as

$$P_{I\mathrm{out}}^{\mathsf{LMMSE}} = 1 - F_1^{\mathsf{MMSE}}F_2^{\mathsf{MMSE}}, \quad (15)$$

where

$$F_1^{\mathsf{MMSE}} = \frac{\Gamma\left(N,\frac{d_1^\tau\gamma_{\mathsf{th}}}{(1-\theta)\rho_1}\right)}{\Gamma(N)} - \frac{e^{-\frac{d_1^\tau\gamma_{\mathsf{th}}}{(1-\theta)\rho_1}}(1-\theta)\rho_I}{d_I^\tau\Gamma(N)}\times \left(\frac{d_1^\tau\gamma_{\mathsf{th}}}{(1-\theta)\rho_1}\right)^N {}_2F_1\left(2,1;2;-\frac{d_1^\tau\rho_I}{d_I^\tau\rho_1}\gamma_{\mathsf{th}}\right), \quad (16)$$

and $F_2^{\mathsf{MMSE}} = F_2^{\mathsf{MRC}}$.

Proof: Due to space limitation, the proof is omitted. □

To gain further insights, we now look into the high SNR region, and present a simple approximation for the outage probability.

Theorem 4: In the high SNR region of $\rho_1 \to \infty$, outage probability of the MMSE/MRT scheme can be approximated as in (17) shown on the top of the next page.

Proof: Due to space limitation, the proof is omitted. □

Theorem 4 indicates that the MMSE/MRT scheme achieves a diversity order of N, the same as the MRC/MRT scheme. Moreover, it can be shown that the MMSE/MRT scheme always achieves a strictly better outage performance than the MRC/MRT scheme (this result can be obtained by following the same steps as in the proof of the Corollary 3 in [21]).

2) Optimal θ Analysis in the High SNR Region: Also, we focus on the outage performance in the high SNR region. Based on the high SNR approximation for $P_{I\mathrm{out}}^{\mathsf{MMSE}}$ in (17), the optimal θ can be found as:

Proposition 2: The optimal θ is a root of the following equation

$$\frac{1}{(1-\theta)^{N+1}\Gamma(N)} + \frac{(N-1)\rho_I}{d_I^\tau(1-\theta)^N\Gamma(N)} - \frac{\mathcal{B}}{\theta^{N+1}} = 0, \quad (18)$$

where $\mathcal{B}$ have been defined in (11) and $0<\theta<1$.

Proof: The result is derived by following the same steps as in the proof of Proposition 1. □

IV. Numerical Results and Discussion

We now present numerical results to validate the analytical expressions presented in Section IV, and investigate the impact of various key system parameters on the system's performance. Unless otherwise specify, we set $\gamma_{\mathsf{th}} = 0$ dB, $\eta = 0.8$, $\theta = 0.5$, $\rho_I = 9.5$ dB, $\tau = 2$ and $d_1 = d_2 = d_I = 1$.

$$P_{I\text{out}}^{\text{MMSE}} \approx \left(\frac{d_1^\tau \gamma_{\text{th}}}{\rho_1}\right)^N \left(\frac{\left(\frac{1}{N!} + \frac{(1-\theta)\rho_I}{d_I^\tau \Gamma(N)}\right)}{(1-\theta)^N} + \frac{\left(\frac{d_2^\tau}{\eta\theta}\right)^N}{N!(N-1)!} \sum_{i=0}^{N-1} \frac{\binom{N-1}{i}(-1)^{N-i-1} {}_2F_1\left(N, 2N-i-1; 2N-i; 1-\frac{d_1^\tau \rho_I}{d_I^\tau \rho_1}\right)}{2N-i-1} \right). \tag{17}$$

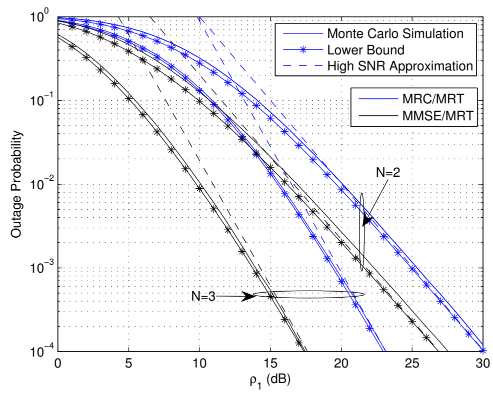


Fig. 2. Impact of N on the system performance.

Fig. 2 illustrates the impact of antenna number N on the outage probability. It can be readily observed that for both considered schemes, the proposed lower bounds are sufficiently tight across the entire SNR range of interest, especially when N is large, and become almost exact in the high SNR region, while the high SNR approximations work quite well even at moderate SNR values (i.e., $\rho_1 = 15$ dB). In addition, we see that both the MRC/MRT and MMSE/MRT schemes achieve the full diversity order of N, and the MMSE/MRT scheme outperforms the MRC/MRT scheme by attaining a higher array gain, which is consistent with our analytical results.

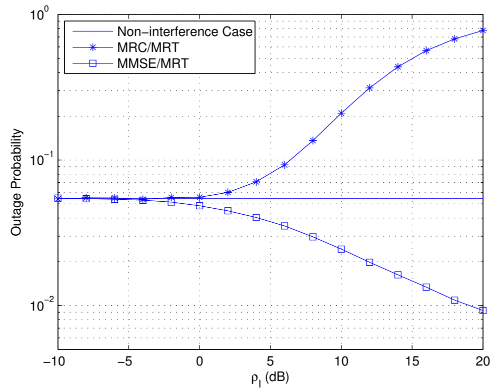
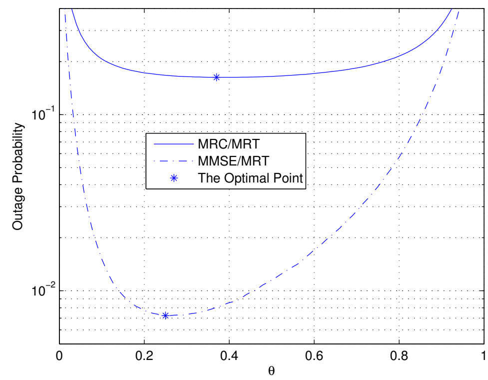
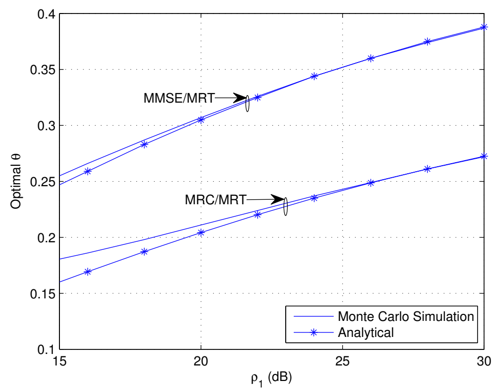


Fig. 3. Impact of CCI on the system performance.

Fig. 3 investigates the impact CCI on the system performance. The scenario without CCI is also plotted for comparison. It can be readily observed that the outage probability of the MRC/MRT scheme decreases slightly for smaller ρ_I (i.e., $\rho_I < -4$ dB), and then increases as the interference becomes stronger. This phenomenon clearly indicates that CCI can cause either a beneficial or decremental effect on the outage probability. For the MRC/MRT scheme, when CCI is too strong, the disadvantage of CCI becomes the dominant performance limiting factor. However, with sophisticated interference mitigation schemes, such undesirable effect could be eliminated. As shown in the MMSE/MRT schemes, the outage probability decreases monotonically as ρ_I increases, which indicates that CCI is always desirable when the MMSE/MRT scheme is employed.



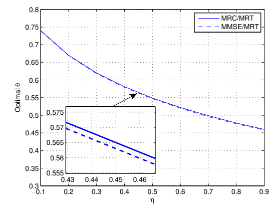
(a) Outage probability versus θ.



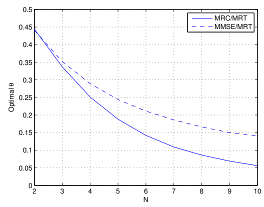
(b) Simulation optimal θ versus analytical optimal θ.

Fig. 4. The optimal power splitting ratio θ.

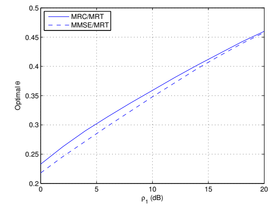
Fig. 4(a) investigates the the impact of the power splitting ratio θ on the outage performance. We observe that there exists a unique θ which gives the best outage performance. For both schemes, we see a similar trends on the impact of θ, i.e., when θ increases from zero to the optimal value, the performance improves; when θ exceeds the optimal values, the performance deteriorates gradually. This phenomenon is rather intuitive, since the performance of dual-hop systems is limited by the weakest hop quality. Moreover, we see that the optimal θ is in general different for different schemes. As shown in this figure, the MMSE/MRT scheme requires a smaller θ compared with the MRC/MRT scheme. The accuracy of the optimal θ obtained through Proposition 1 and 2 is examined in Fig. 4(b). It can be readily observed that, the analytical results based on the high SNR approximation match quite well with the simulation results even at moderate SNR values (i.e., $\rho_1 = 20$ dB).



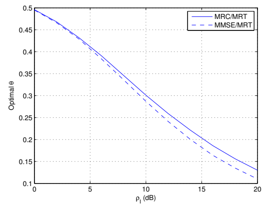
(a) $N = 2$, $\rho_1 = 10$ dB, $\rho_I = 0$ dB



(b) $\eta = 0.8$, $\rho_1 = 10$ dB, $\rho_I = 0$ dB



(c) $N = 2$, $\eta = 0.8$, $\rho_I = 5$ dB



(d) $N = 2$, $\eta = 0.8$, $\rho_1 = 15$ dB

Fig. 5. The impact of (a) η, (b) N, (c) ρ_1, (d) ρ_I on the outage optimal θ.

Fig. 5 examines the effect of various key system parameters such as η, N, ρ_1 and ρ_I on the choice of optimal θ. Specifically, Fig. 5(a) illustrates the effect of η, and we can see that, the outage optimal θ is a decreasing function of η. A large η implies higher energy conversion efficiency, which in turn suggests that less portion of the signal is needed for energy harvesting, hence, a smaller θ is required. A similar trend is observed in Fig. 5(b) on the impact of N. As N increases, the additional antennas improve the energy harvesting capability, which implies that the optimal θ should decrease. The effect of ρ_1 is shown in Fig. 5(c). For both schemes, the optimal θ is an increasing function of ρ_1. Finally, Fig. 5(d) investigates the effect of ρ_I. It is readily to see that the optimal θ is a decreasing function of ρ_I for both schemes. This is intuitive since CCI serves as the energy source, when CCI power increases, a smaller θ is sufficient to fulfill the energy requirement at the relay.

V. Conclusion

We have studied the outage performance of two different linear processing schemes in dual-hop energy harvesting relaying systems in the presence of CCI. New analytical expressions for the outage probability and the diversity order were derived. In addition, the optimal power splitting ratio minimizing the outage probability was characterized, and the impact of various key system parameters, such as η, N, ρ_1 and ρ_I on the optimal θ was examined, which provided useful design insights on the choice of a proper θ under different system configurations. Our results reveal that full diversity of N is achieved by both schemes, and the MMSE/MRT scheme attains a higher array gain compared to the MRC/MRT scheme. Furthermore, We showed that CCI could be potentially exploited to significantly improve the system's performance. For the MRC/MRT scheme, CCI could be either beneficial or detrimental, while for the MMSE/MRT scheme, CCI is always a desirable factor, and the stronger the CCI, the better the performance.

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