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Performance of TAS/MRC Wireless Energy Harvesting Relaying Networks over Rician Fading Channels

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Abstract
This Letter studies performance of a dual-hop decode-and-forward relaying network employing a wireless-powered relay antenna with transmit antenna selection for the first hop and maximal ratio combining for the second hop. Compact expressions for outage probability and upper-bound on channel capacity are derived. Monte Carlo simulation results are given to verify theoretical analyses.

Keywords MIMO · TAS/MRC · Rician · Relay · Energy harvesting

1 Introduction

SWIPT—simultaneous wireless information and power transfer—is now a deciding technology for a wide range of applications. Remotely powered devices using SWIPT are not constrained by internal power source but are directly extracting their energy from propagating radio frequency (RF) signals in which information is collected. Wireless-powered devices are often used in applications such as structural monitoring where they are embedded into a structure making battery replacement very difficult. In addition, for applications that require a large scale deployment of devices, battery replacement on individual nodes becomes impractical to perform.

The Rician distribution is popular for microcellular urban and suburban land-mobile because the line-of-sight (LoS) can usually be established. The multiple-input SWIPT-MIMO wiretap channel is studied in [1] in which a base station (BS), an information-decoding (ID) user and an energy harvesting (EH) user are employed. Their result is a

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transmit covariance matrix that carries out the bargain for ergodic secrecy rate and harvested energy. Furthermore, [2] develops a robustness joint cooperative optimization schemes for SWIPT. The joint power allocation (PA), relay placement (RP) and power splitting (PS) are studied to search for the global optimal solution, which reportedly can improve 64–100% of outage probability, subject to channel condition. Without using diversity, [3] considers the Rician channel to study the effects of LoS path component on a system with dual-hop amplify-and-forward (AF) relays with power-splitting (PS) receivers, where the first and second hops undergo Rician and Rayleigh fading, respectively. Morsi and others [4] comprehensively study wireless information and power transfer over typical fading environments and proposed new scheduling. However, they do not specifically employ a relay system. Optimised training design is performed in [5] over Rician fading, focusing on selecting optimal values for energy transfer such as transfer duration and block length but multiple antennas with a relay are not employed. SWIPT optimisation is performed in [6] and [7] over Rician fading but they do not specifically focus on diversity in their study. Interference in SWIPT systems is reported in [8] which presents another angle at optimising system performance in terms of its outage probability and capacity but diversity is still not thoroughly considered. Detailed performance of multi-input single-output (MISO) SWIPT systems is given in [9], however, a relay is not employed and the destination only employs one receive antenna. Careful studies of the open literature on SWIPT systems in Rician fading shows that system performance in this specific fading environment has not yet been thoroughly performed. In addition, performance of a practical system employing one relay with multiple antennas at both the source and the destination has not been comprehensively studied. This Letter addresses the knowledge gaps in the current literature and focusses on system performance using a transmit antenna selection with maximal ratio combining (TAS-MRC) relaying network in independent and identically distributed (i.i.d.) Rician fading environments. The Letter is organised as follows. Section 2 outlines the system model. Section 3 performs theoretical analyses for outage probability and ergodic channel capacity by deriving their compact expressions. Numerical analyses with detailed simulation results are given in Sect. 4. Section 5 concludes the findings of this Letter and presents possible future work.

2 System and Channel Model

Consider a dual-hop relaying network with an individual Source (S), a Relay (R) and a Destination (D) as shown in Fig. 1. All nodes operate in half-duplex mode, R is equipped with a single antenna, while N_{S} and N_{D} antennas are mounted at S and D respectively. Assuming that the decode-and-forward relay does not have fixed power supply but it is powered by wireless power transferring from S. The wireless channels from the S to R and from R to D are assumed quasi-static independent and identically distributed (i.i.d.) Rician fading, where the fading is also assumed slow during transmission but varies independently from hop to hop.

Considering a time switching energy harvesting model [3], each data frame is subsequently divided into three consecutive time slots for energy transmission, information transmission and information reception. Correspondingly, the duration for each time slot is αT, $\frac{1-\alpha}{2}T$ and $\frac{1-\alpha}{2}T$ respectively, where $\alpha \in [0, 1]$ and T denotes the total period of a data frame. In the first and second time-slots under TAS diversity scheme, R receives a signal from S and harvests a fraction of energy from its received signal power. The harvested energy is

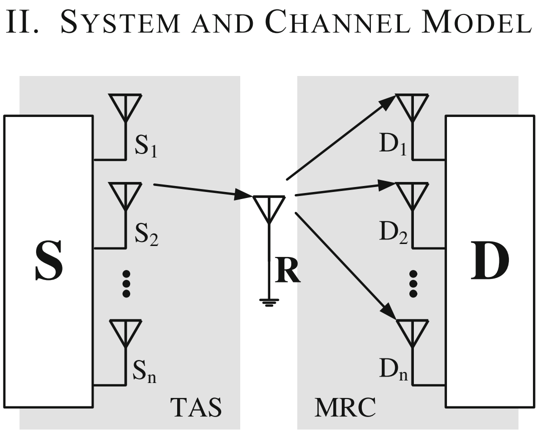

Fig. 1 A TAS/MRC relaying system with SWIPT

$$E_H = \varepsilon P_{\mathsf{S}} \left|h_{1,i^*}\right|^2 \alpha T, \tag{1}$$

where ϵ is the energy harvesting efficiency and P_{S} is the average transmit power of S. In (1), h_{1,i^*} is the strongest channel coefficient of the first hop due to TAS, where $i^* = \arg\max_{i=1\ldots N_{\mathsf{S}}} \left|h_{1,i}\right|^2$. As a result, the instantaneous signal to noise ratio (SNR) of the first hop is given by

$$\gamma_1 = \frac{P_{\mathsf{S}}}{N_0} \left|h_{1,i^*}\right|^2, \tag{2}$$

where N_0 is the additive white Gaussian noise (AWGN) power. In the third time-slot, R uses all harvested energy to decode the received signal and then forwards the re-encoded signal to D. Under MRC diversity scheme at D, the SNR of the second hop is given by

$$\gamma_2 = \sum_{j=1}^{N_{\mathsf{D}}} \frac{P_{\mathsf{R}}}{N_0} \left|h_{2,j}\right|^2 = \frac{2\varepsilon\alpha P_{\mathsf{S}}}{(1-\alpha)N_0} \left|h_{1,i^*}\right|^2 \sum_{j=1}^{N_{\mathsf{D}}} \left|h_{2,j}\right|^2, \tag{3}$$

where $h_{2,j}$ is the channel coefficient from R to antenna j of D. For dual-hop DF relaying, the end-to-end SNR of the system can be given as [10] $\gamma_\Sigma = \min(\gamma_1, \gamma_2)$. Since signal transmission is dependent on the harvested energy, it should be noted from (2) and (3) that γ_1 and γ_2 are correlated because of the common term $\left|h_{1,i^*}\right|^2$, as such, statistics of the output SNR after implementing TAS and MRC plays important roles in assessing system performance.

3 Performance Analysis

3.1 TAS/MRC over Rician Fading Channel

The Rice distribution is frequently employed to model fading environments where a dominant LOS component is present along with many other weaker paths. The SNR per symbol of the channel has the Rice distribution [11, p. 46]

$$f(x) = \frac{(1+K)}{\lambda} e^{-\left[K + \frac{(1+K)t}{\lambda}\right]} I_0\left(2\sqrt{\frac{K(1+K)x}{\lambda}}\right), \tag{4}$$

where λ is the average SNR per symbol, I_0 is the zeroth-order modified Bessel function of the first kind which is defined by [11, 2.1–120]

$$I_k(z) = \sum_{m=0}^{\infty} \frac{1}{m!\Gamma(m+k+1)} \left(\frac{z}{2}\right)^{2m+k} \tag{5}$$

and K is the Rician fading factor. The cummulative distribution function (CDF) of Rician fading channel can be expressed as follows [11, 2.1–124]:

$$F(x) = 1 - Q_1\left(\sqrt{2K}, \sqrt{2(1+K)\frac{x}{\lambda}}\right). \tag{6}$$

Under the TAS scheme, the TAS output (TASO) CDF can be given by

$$F^{TAS}(x) = \left[1 - Q_1\left(\sqrt{2K}, \sqrt{2(1+K)\frac{x}{\lambda}}\right)\right]^{N_{\mathsf{S}}}, \tag{7}$$

where N_{S} denotes number of transmit antennas and $Q_1(\cdot,\cdot)$ is the first-order Marcum Q-function which is defined in [11, 2.1–123]. The Marcum Q-function has been thoroughly studied in [12, p. 93–105] and it can be readily implemented in MATLAB. Under the MRC scheme at D, the MRC output (MRCO) CDF can be given by [13, (20)]

$$F^{MRC}(x) = 1 - Q_{N_{\mathsf{D}}}\left(\sqrt{2N_{\mathsf{D}}K}, \sqrt{2(1+K)\frac{x}{\lambda}}\right), \tag{8}$$

where N_{D} is the number of receive antennas.

3.2 Outage Probability

For the time-switching scheme, the ergodic system capacity C is proportional to the duration of the forwarding phase $C = \frac{1-\alpha}{2}\log_2(1+\gamma_\Sigma)$. Given the target rate R, we may write

$$\begin{aligned} \mathrm{OP} &= \Pr\left[\frac{1-\alpha}{2}\log_2(1+\gamma_\Sigma) < R\right] = \Pr[\min(\gamma_1,\gamma_2) < \gamma_{\mathrm{th}}] \\ &= 1 - \Pr[\gamma_1 > \gamma_{th}, \gamma_2 > \gamma_{th}], \end{aligned} \tag{9}$$

where $\gamma_{th} = 2^{\frac{2R}{1-\alpha}} - 1$ is the SNR threshold. Denoting $\beta_1 \triangleq \max_{i=1\ldots N_{\mathsf{S}}} |h_{1,i}|^2 = |h_{1,i^*}|^2$ and $\beta_2 \triangleq \sum_{j=1}^{N_{\mathsf{D}}} |h_{2,j}|^2$, (9) can be given as

$$\mathrm{OP} = 1 - \underbrace{\Pr\left[\beta_1 > \frac{\mathrm{N}_0}{\mathrm{P}_{\mathsf{S}}}\gamma_{\mathrm{th}}, \beta_1\beta_2 > \frac{(1-\alpha)\mathrm{N}_0}{2\varepsilon\alpha\mathrm{P}_{\mathsf{S}}}\gamma_{\mathrm{th}}\right]}_{\mathcal{I}}. \tag{10}$$

Letting $a = \frac{N_0}{P_{\mathsf{S}}}, b = \frac{(1-\alpha)N_0}{2\varepsilon\alpha P_{\mathsf{S}}}$ and using the conditional probability, we have

$$\begin{aligned}\mathcal{I}(\gamma) &= \Pr(\beta_1 > a\gamma, \beta_1\beta_2 > b\gamma) \\ &= \int_{a\gamma}^{\infty} \left[1 - F_{\beta_2}\left(\frac{b\gamma}{x}\right)\right] f_{\beta_1}(x)dx,\end{aligned} \tag{11}$$

where $f_{\beta_1}(x)$ and $F_{\beta_2}(x)$ represent probability density function (PDF) and CDF of β_1 and β_2 respectively. From (8), the CDF of β_1 can be given by

$$F_{\beta_1}(x) = \left[1 - Q\left(\sqrt{2K_1}, \sqrt{2(1+K_1)\frac{x}{\lambda_1}}\right)\right]^{N_S}, \tag{12}$$

where K_1 and λ_1 denote the fading factor and the average SNR of the first hop respectively. Using [14], the PDF of β_1 can be given by

$$\begin{aligned}f_{\beta_1}(x) =& \frac{N_S(1+K_1)}{\lambda_1} e^{-K_1-(1+K_1)\frac{x}{\lambda_1}} \\ &\times \sum_{r=0}^{\infty} \frac{1}{r!\Gamma(r+1)} \left[K_1(1+K_1)\frac{x}{\lambda_1}\right]^r \\ &\times \underbrace{\left[1 - Q\left(\sqrt{2K_1}, \sqrt{2(1+K_1)\frac{x}{\lambda_1}}\right)\right]^{N_S-1}}_{\mathcal{A}}.\end{aligned} \tag{13}$$

Let $a_i = \sum_{j=0}^{i} \frac{\alpha^{2j}}{j!2^j\Gamma(i+L+1)}$, we obtain $1 - Q_L(\alpha,\beta) = e^{-\frac{\alpha^2+\beta^2}{2}} \sum_{i=0}^{\infty} a_i \left(\frac{\beta^2}{2}\right)^{i+L}$, which can be rewritten using [15, eq. 0.314]

$$[1 - Q_L(\alpha,\beta)]^n = e^{-n\frac{\alpha^2+\beta^2}{2}} \sum_{i=0}^{\infty} c_{i1} \left(\frac{\beta^2}{2}\right)^{i+nL}, \tag{14}$$

$$c_{i1} = \begin{cases} \dfrac{1}{\Gamma(L+1)^n}, & i = 0, \\ \dfrac{\Gamma(L+1)}{i} \displaystyle\sum_{k=1}^{i} \sum_{j=0}^{k} \frac{\alpha^{2j}(kn-i+k)}{j!2^j\Gamma(k+L+1)} c_{i-k}, & i \geq 1, \end{cases} \tag{15}$$

so that

$$\mathcal{A} = e^{(1-N_S)\left[K_1+(1+K_1)\frac{x}{\bar{\gamma}_1}\right]} \sum_{i=0}^{\infty} c_{i2} \left[(1+K_1)\frac{x}{\bar{\gamma}_1}\right]^{i+N_S-1}, \tag{16}$$

$$c_{i2} = \begin{cases} 1, & i = 0, \\ \dfrac{1}{i} \displaystyle\sum_{k=1}^{i} \sum_{j=0}^{k} \frac{(K_1)^j(kN_S - i)}{j!(k+1)!} c_{i-k}, & i \geq 1. \end{cases} \tag{17}$$

Substituting (16) into (13), the PDF of the first hop can be given by

$$f_{\beta_1}(x) = \frac{N_\mathsf{S}(1+K_1)}{\lambda_1 e^{N_\mathsf{S}K_1}} e^{-N_\mathsf{S}(1+K_1)\frac{x}{\lambda_1}} \times \sum_{i=0}^{\infty}\sum_{r=0}^{\infty} \frac{c_{i2}K_1^r}{(r!)^2}\left[\frac{(1+K_1)x}{\lambda_1}\right]^{i+r+N_\mathsf{S}-1}, \tag{18}$$

where c_{i2} is given in (17). Using [13, (20)], for the second hop, the CDF of β_2 is given in (19)

$$F_{\beta_2}(x) = 1 - Q_{N_\mathsf{D}}\left(\sqrt{2N_\mathsf{D}K_2}, \sqrt{2(1+K_2)\frac{x}{\lambda_2}}\right), \tag{19}$$

where K_2 and λ_2 represent Rician fading factor and average SNR of the second hop respectively. Using [12, p. 95–97] into (19), F_{β_2} can be rewritten as

$$F_{\beta_2}(x) = 1 - \sum_{m=0}^{\infty}\sum_{k=0}^{m+N_\mathsf{D}-1} \frac{e^{-\left[N_\mathsf{D}K_2+(1+K_2)\frac{x}{\lambda_2}\right]}(N_\mathsf{D}K_2)^m}{m!k!} \times \left[(1+K_2)\frac{x}{\lambda_2}\right]^k. \tag{20}$$

The integral $\mathcal{I}$ therefore can be rewritten as

$$\mathcal{I}(\gamma) = \frac{N_\mathsf{S}(1+K_1)}{\bar{\gamma}_1 e^{N_\mathsf{S}K_1+N_\mathsf{D}K_2}} \sum_{p=0}^{\infty}\sum_{m=0}^{\infty}\sum_{k=0}^{m+N_\mathsf{D}-1}\sum_{i=0}^{\infty}\sum_{r=0}^{\infty} \times \frac{c_i(-1)^p(N_\mathsf{D}K_2)^m(K_1)^r}{m!k!p!(r!)^2} \times \left(\frac{1+K_2}{\bar{\gamma}_2}\right)^{k+p}\left(\frac{1+K_1}{\bar{\gamma}_1}\right)^{i+r+N_\mathsf{S}-1} b^{k+p} \times \underbrace{\gamma^{k+p}\int_{a\gamma}^{\infty} e^{-N_\mathsf{S}(1+K_1)\frac{x}{\bar{\gamma}_1}} x^{i+r+N_\mathsf{S}-k-p-1}dx}_{\mathcal{J}}, \tag{21}$$

where $\mu = \frac{N_\mathsf{S}(1+K_1)}{\bar{\gamma}_1}$. Using [15, (2.325.6)], we obtain

$$\mathcal{J}(\gamma) = \gamma^{k+p}(a\mu)^{k+p-i-r-N_\mathsf{S}}\Gamma(i+r+N_\mathsf{S}-k-p, a\mu\gamma). \tag{22}$$

3.3 Channel Capacity

The Shannon capacity of a channel defines its theoretical upper bound for the maximum rate of data transmission for an arbitrary small BER, without any delay or complexity constraints. Therefore, the Shannon capacity represents an optimistic bound for practical communication schemes. It also serves as a benchmark to compare the spectral efficiency of all practical adaptive transmission schemes [10]. Applying Jensen inequality, an upper bound on the system capacity can be obtained as

$$C = \frac{1-\alpha}{2}\int_0^\infty \log_2(1+\gamma_\Sigma)d\gamma \leq \frac{1-\alpha}{2}\log_2(1+\bar{\gamma}_\Sigma), \tag{23}$$

where the equivalent SNR $\bar{\gamma}_\Sigma$ is computed by substituting (21) into (10) as

$$\begin{aligned}\bar{\gamma}_\Sigma = & \frac{N_{\mathsf{S}}(1+K_1)}{\bar{\gamma}_1 e^{N_{\mathsf{S}}K_1+N_{\mathsf{D}}K_2}}\sum_{p=0}^{\infty}\sum_{m=0}^{\infty}\sum_{k=0}^{m+N_{\mathsf{D}}-1}\sum_{i=0}^{\infty}\sum_{r=0}^{\infty} \\ & \times \frac{c_i(-1)^p(N_{\mathsf{D}}K_2)^m(K_1)^r}{m!k!p!(r!)^2}\left(\frac{1+K_2}{\bar{\gamma}_2}\right)^{k+p} \\ & \times \left(\frac{1+K_1}{\bar{\gamma}_1}\right)^{i+r+N_{\mathsf{S}}-1} b^{k+p}a^{i+r+N_{\mathsf{S}}-k-p} \\ & \times \underbrace{\int_0^\infty \gamma^{i+r+N_{\mathsf{S}}}\mathrm{Ei}_{1+k+p-i-r-N_{\mathsf{S}}}(a\mu\gamma)d\gamma,}_{\mathcal{T}}\end{aligned} \tag{24}$$

where $\mathrm{Ei}(\cdot)$ is the exponential integral [16, (6.5.9)]. Denoting $s = i + r + N_{\mathsf{S}}$ and $t = k + p - i - r - N_{\mathsf{S}}$, we have

$$\begin{aligned}\mathcal{T} &= \textstyle\int_0^\infty \gamma^s \mathrm{Ei}_{1+t}(a\mu\gamma)d\gamma &&= \mu^s \textstyle\int_0^\infty \gamma^{s+t}\Gamma(-t, a\mu\gamma)d\gamma \\ &= \frac{(a\mu)^{-1}}{s+t+1}\int_0^\infty e^{-a\mu\gamma}\gamma^s d\gamma &&= \frac{(a\mu)^{-s-1}}{s+t+1}\Gamma(s+1).\end{aligned} \tag{25}$$

Proof Substituting [16, (6.5.9)], using partial integration by letting $u = \Gamma(-b, \mu x)$ and $dv = x^{a+b}$, and using [15, (8.350.4)], we arrive at (25). □

4 Numerical Results and Discussion

From Fig. 2, interchanging K parameters, i.e. $K_{(1,2)} = [0.1, 1.0]$ for each stage, we present four profiles with different fading severity. Profiles with the same K_1 are perfectly matched over a low-SNR region (<15dB). The higher K_1, the higher the disparity for system outage, especially when the SNR is increased. For example, the first and second profiles start differing from each other at SNR $\approx$ 18dB, whereas the difference of the third and fourth profiles occurs at SNR $\approx$ 16dB.

It should be noted that on the second hop, increasing the number of antennas does not significantly reduce outage probability because channel diversity has more impact on the system. Considering three profiles, each has one antenna on the first hop ($N_{\mathsf{S}} = 1$) and from one to three antennas on the second hop $N_{\mathsf{D}} = [1, 2, 3]$. Coupling with two antennas on the first hop, resulting in channel diversity $N_{\mathsf{S}} = 2$, totalling 6 profiles. From Fig. 3, it can be noted that (i) applying diversity at D, i.e. increasing N_{D}, on the second hop does not markedly reduce the OP, (ii) increasing N_{S} significantly reduces the OP as seen in profiles (4)–(6), this improvement is evidently better than that by increasing N_{D} as seen in profiles (1)–(3), (iii) increasing N_{D} typically reduces the OP, however, the effects of N_{D} appears to

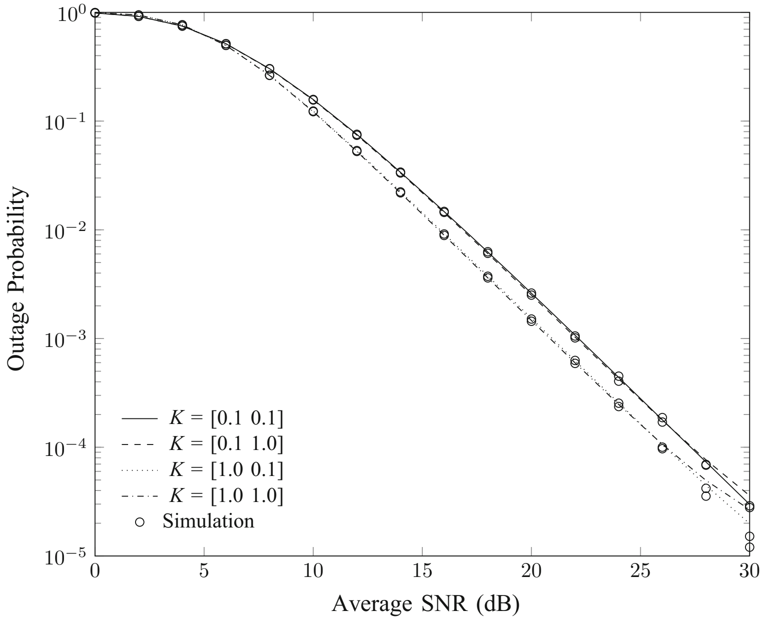

Fig. 2 Effect of fading severity on outage probability, $\lambda_1 = \lambda_2 = 3$, $N_S = N_D = 2$, $\epsilon = 0.75$, $\alpha = 0.5$, $R = 1$, $p_{\max} = m_{\max} = r_{\max} = 10$ and $i_{\max} = 25$

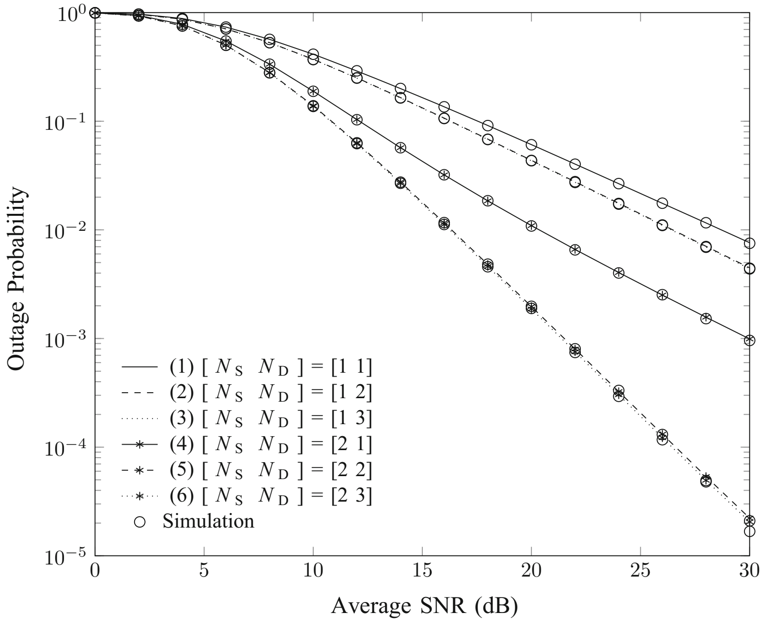

Fig. 3 Effect of channel diversity on outage probability, $[K_1, K_2] = [0.6, 1.2]$, $\lambda_1 = \lambda_2 = 3$, $\epsilon = 0.75$, $\alpha = 0.5$ and $R = 1$

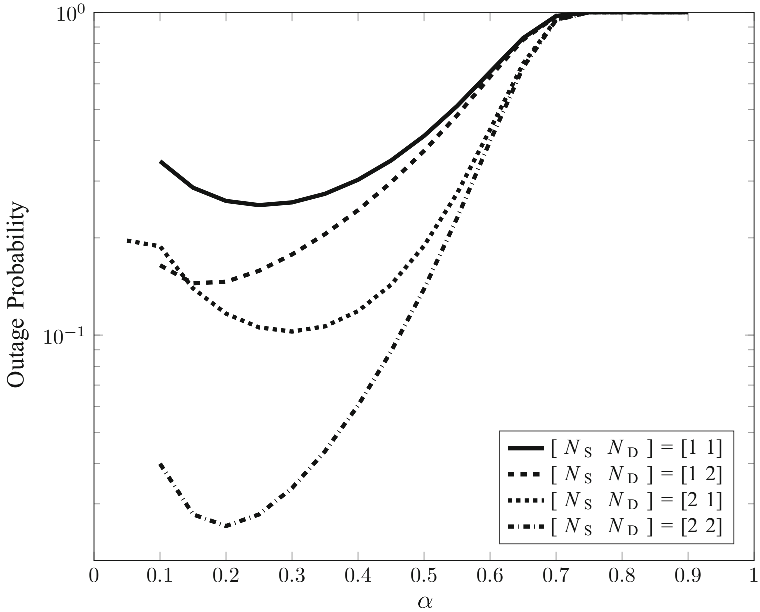

Fig. 4 Effect of harvesting time on outage probability, $[K_1, K_2] = [0.6, 1.2]$, $\lambda_1 = \lambda_2 = 3$, $\epsilon = 0.75$, SNR = 10dB and $R = 1$

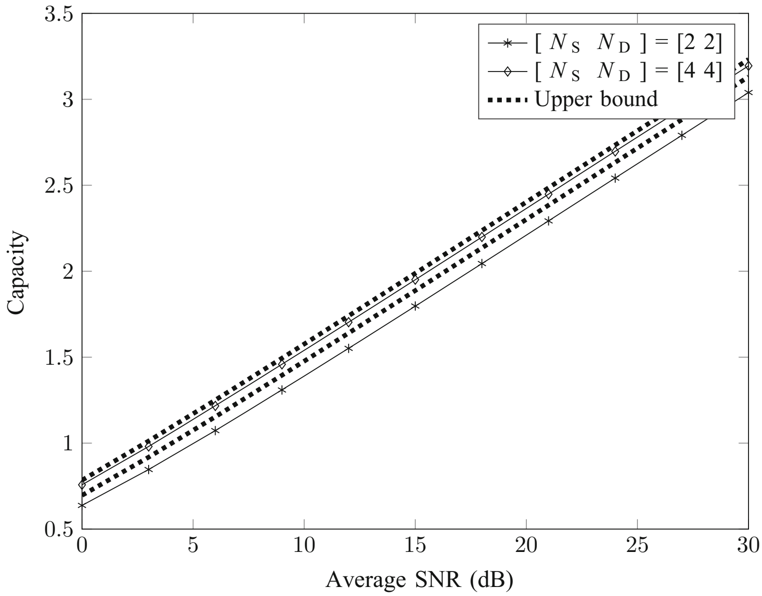

Fig. 5 Upper bound of system capacity, $[K_1, K_2] = [0.6, 1.2]$, $\lambda_1 = \lambda_2 = 4$, $\epsilon = 0.75$, $R = 1$ and $p_{\max} = m_{\max} = r_{\max} = i_{\max} = 25$

saturate for $N_D \geq 2$ as seen in the simulated OP for profiles (5) and (6), which may suggest that the system performance is inversely proportional to the second hop diversity.

From Fig. 4, the outage probability is evaluated against the harvesting time, α. On different profiles, there is always an optimal value of α where OP is minimum. It appears that for $\alpha \geq 0.7$, the OP approaches its maximum which suggests that optimal harvesting should occur at $\alpha \approx 0.35$ which seems reasonable if diversity is applied at the source. The minimum-OP value varies on different profiles and its theoretical value requires complicated mathematical optimisation which is omitted in this Letter for brevity.

Figure 5 shows the approximate channel capacity and its upper bounds using (23) and (24) from which it is evident that simulation and approximation value are consistent, meanwhile the bounds become tighter when the diversity order is increased.

5 Conclusions

Wireless information and power transfer in dual hop relaying networks with multiple antennas at the source and the destination in i.i.d. Rician fading have been studied in this paper. New expressions for the system outage probability and upper-bound on channel capacity have been developed. It is observed that implementing diversity in the first hop has higher impact on system performance than on second hop. New findings on system performance using other diversity schemes will be published in a separate publication.

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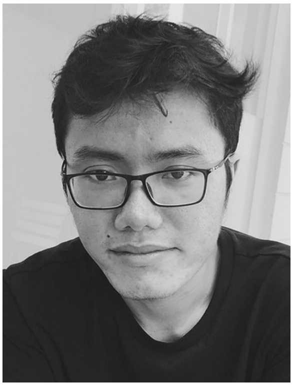

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