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Non-orthogonal multiple access and beamforming for relay network with RF energy harvesting

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Abstract

Downlink multi-user non-orthogonal multiple access (NOMA) relay systems, that are wirelessly powered by harvesting energy from radio frequency, are taken into consideration. To enhance the performance of the NOMA multiuser systems, the base station (BS) is equipped with multiple antennas to make a beamforming for transmitting information signal and energy. The close-form outage probability expressions of proposed system over Rayleigh fading channels are derived and the analytical analysis is verified by computer simulations.

Keywords: Non-orthogonal multiple-access; Energy harvesting; Radio frequency; Successive-interference cancellation; Beamforming

1. Introduction

The non-orthogonal multiple access (NOMA) systems which combine radio frequencies (RF) energy harvesting (EH) are investigated in [1,2]. In those research works, simultaneous wireless information and power transfer (SWIPT) of NOMA networks with randomly located users are studied. The authors in [3] analyzed the system, in which near NOMA users that are close to the source act as energy harvesting relays to help far NOMA users. Meanwhile, the EH from the RF has emerged as a suitable solution for energy-constrained electronic devices, which are often supported by limited power sources such as batteries.

On the other hand, the relay communication and RF EH topics have been widely studied in both academics and research institute. Consequently, there have been many works that have been published. The authors in [4] derive a closed-form expression of the outage probability of the dual-hop decode-and-forward (DF) relaying network, where utilizing the time switching (TS)-based relaying mechanism. The outage probability of the dual hop multiple antennas relying system transferring wireless power is investigated. In [5], the authors proposed a dual-hop multiple antennas amplify-and-forward relaying system with interference for both the fixed-gain and variable-gain relaying schemes. The optimal throughput of MIMO full duplex system is proposed in [6]. In this work, the antennas are configured at the relay, leading to the fact that the energy consumption at the relay is increased with the number of antennas. To the best of author's knowledge, there is a lack of study in the combination of TS with NOMA relaying network systems, consequently, in this paper, we propose combination of TS with NOMA. Moreover, in order to cancel the inter-cluster interference, a beamforming method is proposed to combine with TS and NOMA method for downlink multi-user system. The contributions of the paper are summarized as follows.

- To prolong the time-life of the system and improve spectrum coefficient, we focus on the downlink NOMA system with multiple antennas at the base station (BS). Several users are clustered to become a group based on the their location. To mitigate the crisscross interference from the other clusters, the zero-forcing beamforming method is applied to the BS.
- The system performance is analyzed theoretically, and close-form expressions of outage probability for each user at an arbitrary group are derived in order to evaluate the proposed system model. We compare the simulation

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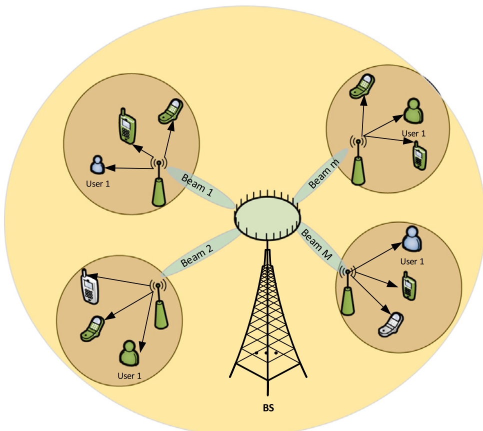

Fig. 1. System model.

result with calculation result to confirm the close-form expressions.

The rest of the paper is organized as follows. Section 2 presents the multi-user NOMA system model and channel model. The performance analysis is given in Section 3. Numerical results are presented in Section 4. Finally, Section 5 concludes the work.

2. System model

2.1. Combination of beamforming and NOMA for the first hop

We consider a downlink multi-user (MU) relay communication network, where a BS communicates with users by assistance of M relays (R) as shown in Fig. 1. The relays perform the EH from the RF to forward the received signal from the BS to users. The BS and every relay are respectively configured by N_t and N_r antennas with condition that $N_t \geq (M-1)$. It is considered as massive antenna at the BS, while the users have a single antenna due to the size limitation. Let $x_{S,m}$ denote the transmit signal for all users in the mth cluster. Before transmission, the symbol $x_{S,m}$ must be multiplied by an $N_t \times 1$ normalized beamforming vector $\mathbf{w}_m$, $\|\mathbf{w}_m\|^2 = 1$.

The perfect CSI at the BS is difficult due to both causes, i.e., channel estimation error and feedback delay. Hence, the relation between the estimated channel matrix $\hat{\mathbf{h}}_m$ and the actual channel matrix $\mathbf{h}_m$ can be given as

$$\mathbf{h}_m = \hat{\mathbf{h}}_m + \mathbf{e}, \tag{1}$$

where $\mathbf{e}$ is the channel estimation error vector with independent and identically distributed (i.i.d.) zero mean and unit variance complex Gaussian distributed entries.

To keep a balance between complexity of implementation and performance of system, we use zero-force beamforming (ZFBF) at the BS. We design a weight $\mathbf{w}_m$ for the mth cluster to mitigate the interference from the other clusters.

The channel matrix between the BS and the mth cluster is denoted by $\mathbf{h}_m \in \mathbb{C}^{N_r \times N_t}$ The channel coefficients are denoted by $\mathrm{h}_m \sim \mathcal{CN}(0, \Omega_m)$, where $\mathbb{E}\{|\mathrm{h}_m|^2\} = \Omega_m$ are variance of channel gains, and $\mathbb{E}\{\cdot\}$ denotes the average operator. $\mathbf{w}_m$ can be represented as the projection of $\mathbf{h}_m$ in the null space of the interference channels related to the mth cluster in order to maximize the channel gain while canceling the inter-cluster interference. Mathematically, $\mathbf{w}_m$ is given as

$$\mathbf{w}_m = \frac{\Pi_m \mathbf{h}_m}{\|\Pi_m \mathbf{h}_m\|}, \tag{2}$$

where $\Pi_m = \mathbf{I}_N - \mathbf{H}_m(\mathbf{H}_m^H \mathbf{H}_m)^{-1}\mathbf{H}_m^H$, and $\mathbf{H}_m$ is an extended channel matrix that excludes $\mathbf{h}_m$.

$$\mathbf{H}_m = [\mathbf{h}_1, \mathbf{h}_2, \ldots, \mathbf{h}_{m-1}, \mathbf{h}_{m+1}, \ldots, \mathbf{h}_M]^T, \tag{3}$$

The signals can be transmitted to the mth relay in case the null space of $\mathbf{H}_m$ has one dimension greater than zero. Thus we have

$$\mathbf{h}_m^H \mathbf{w}_j = 0, \forall m \neq j. \tag{4}$$

Moreover, we assume that the number of sensors in every cluster is the same as N, and hence every antenna of the BS transmits the superposition code, which includes N signals of all users in the mth cluster, it can be described by $\mathbf{x}_{S,m} = [x_{m,1}, \ldots, x_{m,N}]^T$, where $x_{m,n}$ is the signal of the nth user in the mth cluster, (hereafter called (m,n)th user), $\mathbb{E}\{|\mathbf{x}_{S,m}|^2\} = P_S$ and $[\cdots]^T$ denotes the transpose matrix. The superposition signals are constructed with beam vector, $\mathbf{w}_m$, at the output antenna based on the principle of ZFBF. Hence the signals intended to the mth cluster are given by

$$\mathbf{x}_{S,m} = \mathbf{w}_m \sum_{n=1}^{N} \sqrt{a_{m,n} P_S}\, x_{m,n}, \tag{5}$$

where $a_{m,n}$ denotes the power allocation coefficient for the (m,n)th user and $\sum_{n=1}^{N} a_{m,n} = 1$.

The $M \times 1$ vector $\mathbf{x}_S$ is broadcast over single cell to all relays. The signal received at the mth relay can be given as

$$y_R = \underbrace{\mathbf{h}_m \mathbf{w}_m \sum_{n=1}^{N} \sqrt{a_{m,n} P_S}\, \mathbf{x}_{S,m}}_{m\text{th beam}} + \underbrace{\sum_{j=1 \neq m}^{M} \mathbf{h}_m \mathbf{w}_j \sum_{n=1}^{N} \sqrt{a_{j,n} P_S}\, \mathbf{x}_{S,j}}_{\text{other beam}} + \mathbf{n}_m. \tag{6}$$

Without loss of generality, we assume that beam is perfect, therefore the inter-cluster interference is canceled, and then the received signal at the mth relay is given as

$$\begin{aligned} y_{m,R} &= \mathbf{h}_m \mathbf{w}_m \sum_{n=1}^{N} \sqrt{a_{m,n} P_S}\, \mathbf{x}_{S,m} + \mathbf{n}_{m,n} \\ &= \underbrace{\mathbf{h}_m \mathbf{w}_m \sqrt{a_{m,n} P_S}\, x_{m,n}}_{\text{desired signal of } (m,n)\text{th user}} + \underbrace{\mathbf{h}_m \mathbf{w}_m \sum_{i=n+1}^{N} \sqrt{a_{m,i} P_S}\, x_{m,i}}_{\text{interference of other users}} \\ &\quad + \underbrace{\mathbf{h}_m \mathbf{w}_m \sum_{k=1}^{n-1} \sqrt{\xi_1 a_{m,k} P_S}\, x_{m,k}}_{\text{interference of imperfect SIC}} + \mathbf{n}_m, \end{aligned} \tag{7}$$

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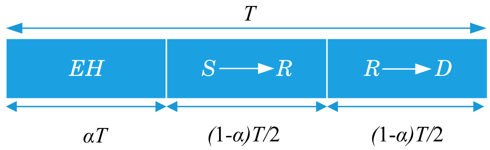

Fig. 2. Time Switching-based Relaying (TSR) protocol.

where $\mathbf{n}_m = [n_1, \ldots, n_{N_r}] \in \mathbb{C}^{1\times N_r}$ with $n_m \sim \mathcal{CN}(0, \sigma_m^2)$ is an i.i.d. additive white Gaussian noise (AWGN) at the mth relay. In case of perfect SIC, the term $\mathbf{h}_m \mathbf{w}_m \sum_{k=1}^{n-1} \sqrt{a_{m,k} P_{\mathrm{S}}} x_{m,k}$ is equal to zero.

2.2. Signal processing at user site

The authors in [7] have shown that, the TS scheme is not only more easily implemented but performs better than the power splitting (PS) scheme for EH-enabled multi-user MIMO networks. Hence, in this work we apply the TS scheme for EH. The details of TS architecture for relay systems are illustrated in Fig. 2. In this figure, T is a block time which is split into three time slots. The first slot, αT $(0 \le \alpha \le 1)$ is used for energy harvesting at relays. The remaining block time, $(1-\alpha)T$, is divided into two equal slots, the first half, $(1-\alpha)T/2$, is used for the S-to-R information transmission, while the second half is used for the R-to-D information transmission.

We assume that the energy is only harvested from the received signal during αT in each period, and total of harvested energy is immediately used to transfer the received signal. Hence, the harvested energy is given by [8, Eq. (2)].

$$E_h = \alpha T \eta P_{\mathrm{S}} |\mathbf{h}_m \mathbf{w}_m|^2, \tag{8}$$

where η is the energy conversion efficiency whose value depends on the quality of the harvester, $0 < \eta < 1$.

Consequently, the transmit power of relays is given by

$$P_{\mathrm{R}} = \frac{2\alpha\eta P_{\mathrm{S}}}{(1-\alpha)} |\mathbf{h}_m \mathbf{w}_m|^2 = \phi P_{\mathrm{S}} |\mathbf{h}_m \mathbf{w}_m|^2, \tag{9}$$

where $\phi = 2\alpha\eta/(1-\alpha)$.

Because the transmission power of the relays is according to quantity of EH, it is always smaller than transmission power of the source. Hence, the transmit power for every user is reallocated to keep the fairness for all users. The allocated power of relay for the (m, n) user is denoted by $b_{m,n}$, and the received signal of the (m, n)th user is given as

$$y_{D_n} = \underbrace{g_n \sqrt{b_n P_{\mathrm{R}}} x_m}_{\text{desired signal of } (m,n)\text{th user}} + \underbrace{g_n \sum_{i=n+1}^{N} \sqrt{b_i P_{\mathrm{R}}} x_i}_{\text{interference of other users}} + \underbrace{\sum_{k=1}^{n-1} \sqrt{\xi_2 b_k P_{\mathrm{R}}} g_n x_k}_{\text{interference of imperfect SIC}} + n_{m,n}. \tag{10}$$

3. Performance analysis

3.1. Signal to interference plus noise ratio

At the relays, the SIC is applied to remove the interference from the other users which have stronger power, i.e., the interference signal of $(i = 1, \ldots, n-1)$th users is removed. The signal interference noise ratio (SINR) of (m, n)th user at the relay is denoted by $\gamma_{m,n}$, and from (7), the SINR is given as

$$\gamma_{m,n} = \frac{P_{\mathrm{S}} a_{m,n} |\mathbf{h}_m \mathbf{w}_m|^2}{\sum_{i=n+1}^{N} P_{\mathrm{S}} a_i |\mathbf{h}_m \mathbf{w}_m|^2 + \sigma_m^2}. \tag{11}$$

Similarly, from (10), the SINR of (m, n)th user in the case of perfect SIC can be given as

$$\gamma_{D_n} = \frac{P_{\mathrm{R}} b_n |g_n|^2}{\sum_{i=n+1}^{N} b_i P_{\mathrm{R}} |g_n|^2 + \sigma_{D_n}^2}. \tag{12}$$

For the DF protocol, the end-to-end SINR of the system is the minimum value between two hops BS $\to R$ and R $\to D_n$, that means

$$\gamma_{e2e} = \min(\gamma_{m,n}, \gamma_{D_n}). \tag{13}$$

3.2. Outage probability

The OP is defined as the probability that makes the transmission rate of the system fall below the minimum required data rate. Let $r_m, r_{m,n}$ bit/s/Hz be the minimum required data rate from BS $\to R_m$ and $\mathrm{R}_m \to D_n$, respectively. For simplicity, we set $r_m = r_{m,n} = r$, thus the OP of the system is calculated as

$$\begin{aligned} \mathrm{OP}_{D_n} &= \Pr\Big[\frac{1-\alpha}{2} \log_2\Big(1 + \gamma_{e2e}\Big)\Big] \\ &= \Pr\Big(\gamma_{e2e} < 2^{\frac{2r}{1-\alpha}} - 1\Big) \end{aligned} \tag{14}$$

Substituting γ_{e2e} in (13) into (14) we have OP of (m, n)th user as

$$\begin{aligned} \mathrm{OP}_{D_n} &= \Pr\Big[\min(\gamma_{\mathrm{R}_n}, \gamma_{\mathrm{D}_n}) < \gamma_{\mathrm{th}}\Big] \\ &= 1 - \Pr\Big(\gamma_{\mathrm{R}_n} \ge \gamma_{\mathrm{th}}, \gamma_{\mathrm{D}_n} \ge \gamma_{\mathrm{th}}\Big), \end{aligned} \tag{15}$$

where $\gamma_{\mathrm{th}} = 2^{\frac{2r}{1-\alpha}} - 1$. From SNR equations that are given in (11) and (12) we have the outage probability in case of perfect SIC as in (16), it is shown in Box I.

Based on the cumulative distribution function (CDF) and probability density function (PDF) of both hops, we derive the outage probability as follows. From (16) we can rewrite as

$$\mathrm{OP}_{D_n} \triangleq 1 - \Pr\Bigg(X \ge \frac{\gamma_{\mathrm{th}} \sigma_{\mathrm{R}}^2}{P_{\mathrm{S}}(a_n - \gamma_{\mathrm{th}} \tilde{a})}, XY \ge \frac{\gamma_{\mathrm{th}} \sigma_{\mathrm{D},n}^2}{P_{\mathrm{S}} \phi (b_n - \gamma_{\mathrm{th}} \tilde{b})}\Bigg), \tag{17}$$

where $\phi = \frac{2\alpha\eta}{1-\alpha}$, $\tilde{a} = \sum_{i=n+1}^{N} a_i$ and $\tilde{b} = \sum_{i=n+1}^{N} b_i$. The $\triangleq$ has mean that, the $a_n > \gamma_{\mathrm{th}} \tilde{a}$ and $b_n > \gamma_{\mathrm{th}} \tilde{b}$ need to satisfy. Otherwise, $a_n \le \gamma_{\mathrm{th}} \tilde{a}$ and $b_n \le \gamma_{\mathrm{th}} \tilde{b}$ the outage always occurs. Hence the allocated power for D_n is more than the others.

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$$\mathrm{OP}_{D_n} = 1 - \Pr\left(\frac{P_{\mathrm{S}} a_n |\mathbf{h}_m \mathbf{w}_m|^2}{\sum_{i=n+1}^{N} P_{\mathrm{S}} a_i |\mathbf{h}_m \mathbf{w}_m|^2 + \sigma_{\mathrm{R}}^2} \geq \gamma_{\mathrm{th}}, \frac{P_{\mathrm{R}} b_n |g_n|^2}{\sum_{i=n+1}^{N} b_i P_{\mathrm{R}} |g_n|^2 + \sigma_{\mathrm{D},n}^2} \geq \gamma_{\mathrm{th}}\right), \tag{16}$$

Box I.

Thank to the help of the property of joint two random variable probability [9], we have

$$\begin{aligned}\mathrm{OP}_{D_n} &= 1 - \int_u^{\infty}\left[1 - F_Y\left(\frac{v}{x}\right)\right] f_X(x)dx \\ &= 1 - \int_u^{\infty} f_X(x)dx + \int_u^{\infty} F_Y\left(\frac{v}{x}\right) f_X(x)dx,\end{aligned} \tag{18}$$

where $u = \frac{\gamma_{\mathrm{th}}\sigma_{\mathrm{R}}^2}{P_{\mathrm{S}}(a_n - \gamma_{\mathrm{th}}\tilde{a})}$ and $v = \frac{\gamma_{\mathrm{th}}\sigma_{\mathrm{D},n}^2}{P_{\mathrm{S}}\phi(b_n - \gamma_{\mathrm{th}}\tilde{b})}$.

Thank to the help of [10, Eq. (3.471.9)] we obtain approximation as

$$\begin{aligned}\mathrm{OP}_{D_n} \approx& \frac{N!}{(N-n)!(n-1)!}\sum_{j=0}^{N-n}\frac{(-1)^j}{n+j}\binom{N-n}{j} \\ &\times \sum_{\ell=0}^{n+j}(-1)^{\ell}\binom{n+j}{\ell}\frac{1}{\Gamma(K)[(1-\rho)\Omega_{\mathrm{SR}}]^K} \\ &\times 2\left(\frac{\ell v \Omega_{\mathrm{SR}}}{\Omega_{\mathrm{RD}_j}}\right)^{\frac{K}{2}}\mathcal{K}_K\left(\sqrt{\frac{4\ell v}{(1-\rho)^2\Omega_{\mathrm{SR}}\Omega_{\mathrm{RD}_j}}}\right),\end{aligned} \tag{19}$$

where $\mathcal{K}_K$ denote the modified Bessel function of the second kind order K.

4. Numerical results

In this section, typical numerical results are provided to analyze the performance of the SWIPT-NOMA system in terms of the outage probability. The simulation parameters are set as follows. The threshold data rates of D_n are $r_1 = r_2 = r_3 = 1$ [b/s/Hz]. The energy conversion efficiency coefficient of relays $\eta = 0.85$. The number of relay nodes $M = 3$ and each cluster has three users. The power allocation coefficient of the (m, n)th user $a_{m,n} = (N - n + 1)/\mu$, where μ is chosen such that $\sum_{n=1}^{N}\sqrt{a_n P_S} = 1$. To simplify the system design and settings, we select the power allocation coefficient at the BS and the relay nodes are the same.

In Fig. 3, we present the outage probability of each user versus SNR in dB. In this figure, we can recognize that the performance of the user 3 is the best among users, although the power allocated for the user 3 is the lowest. This reason is the user 3 is closest to the relay, i.e., the channel gain from the relay to the user 3 is the largest. The interference from other users is canceled completely by SIC scheme, hence the SNR of the user 3 is much higher than SINR of other users. Moreover, the approximation result is close to the simulation at the mean and high SNR, it is justifiable with our assumption above. The approximation of user 1 is the best, because the power allocation for user 1 is the largest. The perfect match between simulation and theoretical results verifies our analysis.

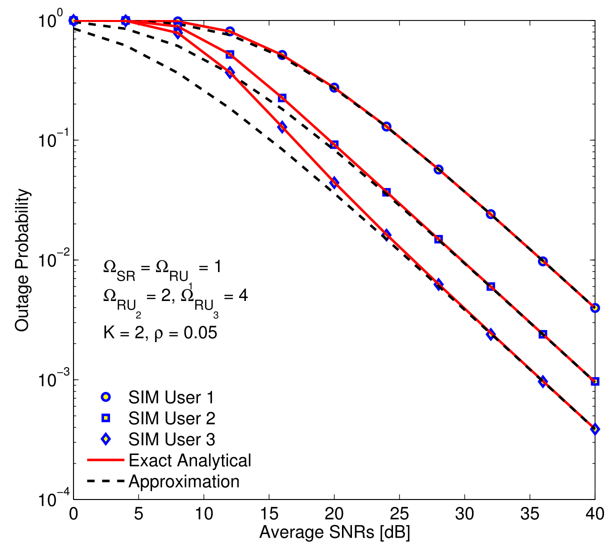

Fig. 3. Outage probability versus SNRs of each user with fraction energy harvesting $\alpha = 0.3$, $\eta = 0.85$, $a_1 = 0.6, a_2 = 0.3, a_3 = 0.1$.

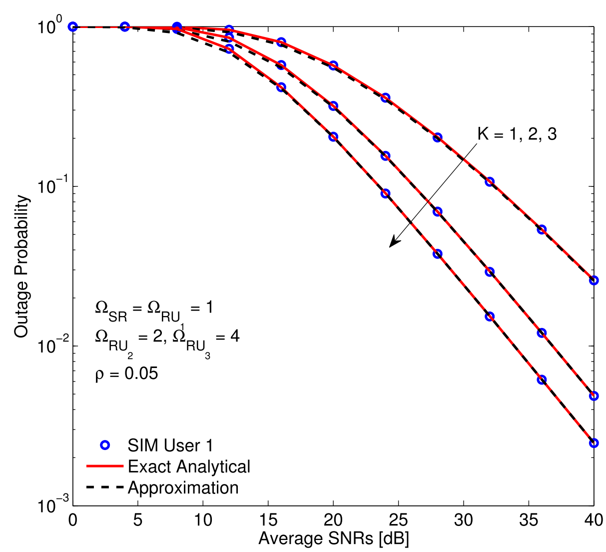

Fig. 4. Outage probability versus SINRs with difference in the number of received antennas, $\alpha = 0.3$, $\eta = 0.85$, $a_1 = 0.6, a_2 = 0.3, a_3 = 0.1$.

Fig. 4 represents the performance of user 1 with varying the number of receive antennas. We can see that increasing the number of antennas leads to improving the performance, the reason is the diversity gains of the first hop are improved. We also see that the analysis results are in excellent agreement with the simulation ones, it confirms the correctness of our proposed analysis approach.

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5. Conclusions

In this paper, the downlink NOMA multi-user network with RF EH was analyzed. The multi-antennas were considered, and then the ZFBF method was applied to cancel the inter-cluster interference. On the other hand, the SIC technology also was applied to cancel the intra-cluster interference. The closed-form expression of outage probability was derived, and the simulation results verified our theoretical analysis.

However, both ZFBF and SIC methods were assumed to be implemented perfectly, hence the inter-cluster and intra-cluster interference were clearly canceled. We will consider the imperfect CSI due to channel estimation error, and then the effect of intra-cluster and inter-cluster interference will be discussed in our future works.

Declaration of competing interest

The authors declare that there is no conflict of interest in this paper.

References

[1] C. Du, X. Chen, L. Lei, Energy-efficient optimisation for secrecy wireless information and power transfer in massive MIMO relaying systems, IET Commun. 11 (1) (2016) 10–16.

[2] R. Sun, Y. Wang, X. Wang, Y. Zhang, Transceiver design for cooperative non-orthogonal multiple access systems with wireless energy transfer, IET Commun. 10 (15) (2016) 1947–1955.

[3] Y. Liu, Z. Ding, M. Elkashlan, H.V. Poor, Cooperative non-orthogonal multiple access with simultaneous wireless information and power transfer, IEEE J. Sel. Areas Commun. 34 (4) (2016) 938–953.

[4] T.M. Hoang, T.T. Duy, V.N.Q. Bao, On the performance of non-linear wirelessly powered partial relay selection networks over rayleigh fading channels, in: Information and Computer Science (NICS), 2016 3rd National Foundation for Science and Technology Development Conference on, IEEE, 2016, pp. 6–11.

[5] L. Gui, Y. Shi, W. Cai, F. Shu, X. Zhou, T. Liu, Design of incentive scheme using contract theory in energy-harvesting enabled sensor networks, Phys. Commun. (2018).

[6] M. Mohammadi, B.K. Chalise, H.A. Suraweera, C. Zhong, G. Zheng, I. Krikidis, Throughput analysis and optimization of wireless-powered multiple antenna full-duplex relay systems, IEEE Trans. Commun. 64 (4) (2016) 1769–1785.

[7] H.H.M. Tam, H.D. Tuan, A.A. Nasir, T.Q. Duong, H.V. Poor, Mimo energy harvesting in full-duplex multi-user networks, IEEE Trans. Wireless Commun. 16 (5) (2017) 3282–3297.

[8] A.A. Nasir, X. Zhou, S. Durrani, R.A. Kennedy, Relaying protocols for wireless energy harvesting and information processing, IEEE Trans. Wireless Commun. 12 (7) (2013) 3622–3636.

[9] A. Papoulis, S.U. Pillai, Probability, RandOm Variables, and Stochastic Processes, Tata McGraw-Hill Education, 2002.

[10] D. Zwillinger, Table of Integrals, Series, and Products, Elsevier, 2014.

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