■ 1907

Exploiting Outage Performance of Wireless Powered NOMA

Dinh-Thuan Do*, Chi-Bao Le
Faculty of Electronics Technology, Industrial University of Ho Chi Minh City (IUH), Vietnam
12 Nguyen Van Bao, Go Vap Dist., Ho Chi Minh City, Vietnam
*Corresponding author, e-mail: dodinhthuan@iuh.edu.vn

Abstract

Considering a dual-hop energy-harvesting (EH) non-orthogonal multiple access (NOMA) relaying system, the main problems are novel relaying protocol based on time power switching-based relaying (TPSR) and power switching-based relaying (PSR) scheme for two kinds of gain factors regarding amplify-and-forward (AF) mode. We introduce novel system model relaying network with impacts of energy harvesting fractions and derive analytical expressions for outage probability with respect to the information transmission link. It confirmed that right selection of power allocation for NOMA, and AF mode to obtain optimal performance as compared study in two considered schemes. The thoughput can be shown its optimal value achieved by numerical method. We also explore impacts of other key parameters of system to outage performance evaluation for different channel models. Simulation results are presented to corroborate the proposed methodology.

Keywords: Non-orthogonal Multiple Access; Energy Harvesting; Outage Probability

1. Introduction

Together with the rapid growth of services and applications in wireless, the demand for increasing power consumption in wireless terminals has dramatically enlarged. Motivated from advantages of various energy harvesting (EH) architectures, relaying network has now been proposed to improve the overall system energy efficiency through considering information transmission and energy-transmission cooperation. The popular energy resources in EH including solar and wind that is intermittent under impacts the environmental alteration, radio frequency (RF) signal is considered as a new viable source which can be applied in wireless power transfer (WPT) [1]. Nevertheless, regarding relay nodes using batteries to power, including mobile devices, because of the short battery lifespan. Besides that, some negative impacts may result from the use of extra energy so it may prevent batteries from performing any relaying. In [2-7], the authors have put forward energy harvesting in relaying networks. For instance, assuming a stationary and ergodic process in terms of energy scavenged by the relay, by taking energy-constrained and energy-unconstrained relays into account, the the symbol error rate was obtained. In this case, from any source the energy could be harvested. The work in [3] focused on two harvest-and-forward protocols relying on either power splitting or time switching, where the relay receives information signal from the source and uses the harvested energy to amplify and forward source signal to the destination. The authors in [4] the wireless energy can be harvested by relays and by interference [5] and the total harvested energy was then allocated for transmissions of signals to different destinations and system performance can be examined in these scenarios. The practical insight into this study is the superior allocation of the total harvested energy among all transmissions. Likewise, by using dual-antenna for simultaneous transmitting and receiving for two-hop three-node network, where energy from the source node is scavenged by the relays. Full-duplex scheme was taken into consideration in [7], where multiple antennas are provided for the relay to carry out energy harvesting process at the source node, therefore, the more bandwidth can be effective implemented.

Consider as a favorable applicant for the fifth generation (5G) wireless networks, non-orthogonal multiple access (NOMA) has been deployed since NOMA can be straightforwardly joint with relaying networks, small cells, device-to-device, cognitive radio networks. At the base station (BS), signals are superimposed as key idea of NOMA in which users' signal with different

power allocation coefficients, and better channel condition together with assigned successive interference cancellation (SIC) to eliminate the other users' signals before distinguishing its own signal [8]. Alternately, a special case of the information theoretic concept, namely *superposition coding,* is similar with the concept of NOMA. Furthermore, user fairness is considered as key feature of NOMA. As compared to conventional water-filling power distribution, worse channel condition is assigned for NOMA with higher power compared with those in case of better channel conditions, trade-off between system throughput and user fairness are improved. As a result, to an increase in spectral efficiency for all users in NOMA where shares the same time slot, frequency and spreading code.

The existing advanced schemes such as multiple-input multiple-output (MIMO) can be included in NOMA as an attractive property in research about NOMA [9]. In different system model, NOMA is studied in cooperative relaying networks (CRS) [10], heterogeneous system [11], and device-to-device (D2D) networks with full-duplex scheme [12]. In other trend, the cooperative NOMA (C-NOMA) together with CRS as investigation in [13] in which spatially multiplexed scheme to serve a single user, while the other papers [9], [11] concentrated on scheme related to a group of users. Outage performance of several relaying networks can be explored in [14-17].

Motivated by these discussions, in this paper we propose two schemes based on kind gain factor in AF mode and analyse a relaying system with WPT under collecting energy from an external energy resource.

The remainder of this paper is organized as follows: Section 2 presents the system model and energy harvesting protocols rea investigated. In Section 3, we derive the analytical expressions of outage probability and throughput in delay-limited transmission. Section 4 examines the simulation results. Finally, Section 5 completes with conclusion remarks for the paper and reviews the important results.

2. System Model

Figure 1 exhibits a cooperative AF relaying network, where the source (S) communicates with two destinations $(D1, D2)$ through an intermediate relay (R). The link between the source and the destination is unreliable or unavailable, so the transmission can only happen successfully with the aid of the wireless powered relay. In particular, the relay node deployed in this paper is characterized as energy-constrained. Furthermore, each node is furnished with a single antenna, and half-duplex mode using amplify-and-forward (AF) strategy is deployed in the relay. The relay acquires two independent data symbols during two time epochs, x_1 from S directly and x_2 through the relay, whereas the EH-NOMA delivers a single data symbol. This paper uses power based relaying energy harvesting (PSR) protocol in Scheme II [2], [3]. We call β is power percentage to energy transfer in such PSR scheme. In particular, during the first phase S broadcasts a superposition-coded signal $a_1 x_1 + a_2 x_2$ to the relay (i.e., R) and the destination nodes including D1 and D2, where P_S represents the total transmit power of the source S, and a_1, a_2 symbolize the power allocation quantity for symbol x_1, x_2 respectively. It can be supposed that D2 is the NOMA-far user from the viewpoint of the source, and therefore, $a_1 < a_2$ to satisfy condition $a_1 + a_2 = 1$. The channel gains between the nodes are modeled as $h_S \sim \mathcal{CN}(0, \Omega_{SR})$ and $h_D \sim \mathcal{CN}(0, \Omega_{RD})$, assumed that all channels follow flat fading Rayleigh distribution.
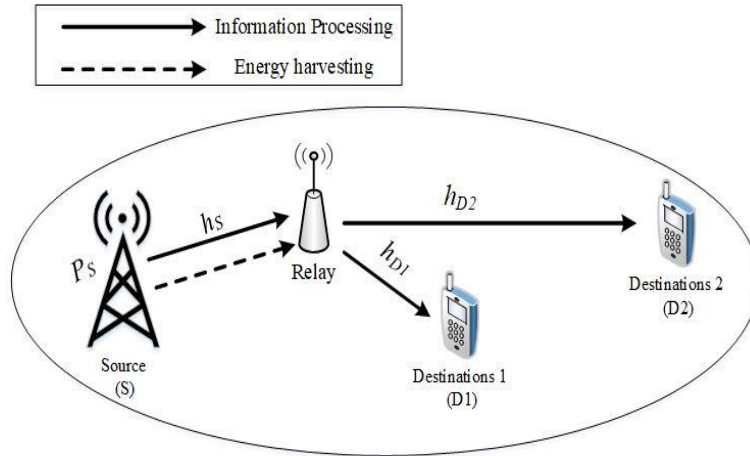
Figure 1. *System model of EH-NOMA*

During the first phase, the received signals at the relay is given by,

$$y_R = \sqrt{(1-\beta)P_S}\, h_S\left(a_1 x_1 + a_2 x_2\right) + n_R, \tag{1}$$

where $n_R \sim \mathcal{CN}\left(0, \sigma^2\right)$ stands for complex additive white Gaussian noise (AWGN) at relay. In this study, we consider two modes:

   (i)   Varying gain based AF and
   (ii) Fixed gain based AF.

Regrading case in SCHEME I, using variable gain in Amplify-and-Forward (AF) mode, the relay will be amplified with factor G as given by $G = 1 / \left(\sqrt{(1-\beta)P_S \left|h_S\right|^2 + \sigma^2} \right)$.

Then, y_D can be expressed as:

$$y_D = \frac{\sqrt{(1-\beta)P_R P_S}\, h_S h_D \left(a_1 x_1 + a_2 x_2\right)}{\sqrt{(1-\beta)P_S \left|h_S\right|^2 + N_0}} + \frac{\sqrt{P_R}\, h_D n_R}{\sqrt{(1-\beta)P_S \left|h_S\right|^2 + N_0}} + n_D, \tag{2}$$

where $n_D \sim \mathcal{CN}\left(0, \sigma^2\right)$ is white Gaussian noise (AWGN) at destination. The harvested energy for signal processing at relay in energy harvesting phase denoted as E_h^{TPSR} re-used in next signal processing $(1-\alpha)T$, and hence the transmit power at relay can be computed as:

$$P_R = \frac{\eta P_S \left|h_S\right|^2 \alpha\beta}{(1-\alpha)}. \tag{3}$$

It is noted that the received signal at destination y_D can be given by:

$$y_D = \underbrace{\frac{\sqrt{\eta\left(P_S \left|h_S\right|^2\right)\alpha\beta(1-\beta)P_S}\, h_S h_D x_S}{\sqrt{(1-\alpha)}\sqrt{(1-\beta)P_S \left|h_S\right|^2 + \sigma^2}}}_{\text{Signal part}} + \underbrace{\frac{\sqrt{\eta\left(P_S \left|h_S\right|^2\right)\alpha\beta}\, h_D n_R}{\sqrt{(1-\alpha)}\sqrt{(1-\beta)P_S \left|h_S\right|^2 + \sigma^2}}}_{\text{Noise part}} + n_D. \tag{4}$$

This paper only considers performance at destination D1 (D2's performance is derived in similar way), the device first decode noise term of D2's signal and then applying SIC to detect its own signal. As a result, it can be obtained specific signal to noise ratio (SNR) for detect D2's signal in approximate form as:

$$\varphi_{D1,x2} \approx \frac{\eta\alpha\beta(1-\beta)P_S|h_S|^2|h_{D1}|^2 a_2^2}{\eta\left(\alpha\beta(1-\beta)P_S|h_S|^2|h_{D1}|^2 a_1^2 + \alpha\beta|h_{D1}|^2\sigma^2\right)+(1-\alpha)(1-\beta)\sigma^2}. \tag{5}$$

Then, D1 perform SIC to detect x_1 signal with the received SNR given by:

$$\varphi_{D1,x1} = \frac{\eta\alpha\beta(1-\beta)P_S|h_S|^2|h_{D1}|^2 a_1^2}{\eta\alpha\beta|h_{D1}|^2 N_0 + (1-\alpha)(1-\beta)\sigma^2}. \tag{6}$$

Similarly, after SIC operation at D2, the receiving SNR for detecting x_2 given by:

$$\varphi_{D2,x2} = \frac{\eta\alpha\beta(1-\beta)P_S|h_S|^2|h_{D2}|^2 a_2^2}{\eta\alpha\beta|h_{D2}|^2 N_0 + (1-\alpha)(1-\beta)\sigma^2}, \tag{7}$$

In SCHEME II, we obtain the fixed gain as:

$$G_2 = \sqrt{\frac{\eta\beta}{1-\beta}}. \tag{8}$$

In this SCHEME, we apply power splitting based energy harvesting as:

$$P_R = \eta\beta P|f|^2. \tag{9}$$

The received signal at D1 can be computed as:

$$\begin{aligned}
y_{D1} &= G_2 h_{D1}\sqrt{1-\beta}\left(\sqrt{P_S}(a_1 x_1 + a_2 x_2)h_S + n_R\right)+n_D \\
&= G_2 h_{D1} f\sqrt{1-\beta}\sqrt{P_S}a_1 x_1 + G h_{D1} f\sqrt{1-\beta}\sqrt{P_S}a_2 x_2 + G_2 h_{D1}\sqrt{1-\beta}n_R + n_D.
\end{aligned} \tag{10}$$

Finallly, we have SNR at D1 before SIC and after SIC respectively as:

$$\gamma_{D1,x2} = \frac{\rho a_2^2|f|^2|g_1|^2}{\rho a_1^2|f|^2|g_1|^2 + |g_1|^2\sigma^2 + b}, \tag{11}$$

And,

$$\gamma_{D1,x1} = \frac{\rho a_1^2|f|^2|g_1|^2}{|g_1|^2\sigma^2 + b}, \tag{12}$$

where $\rho = \dfrac{P_S}{\sigma^2}, b = \dfrac{1}{\eta\beta}$

In next section, the main metric need be examined, i.e. outage behavior. Such outage performance can be considered to compare results of two schemes.

3. Outage Performance Analysis
3.1. SCHEME I

More importantly, the overall outage probability for such EH-NOMA with the proposed TPSR relaying scheme is given by:

$$
\begin{aligned}
OP_{SCHEME1} &= \Pr\left(\varphi_{D1,x2} < \gamma_{th}, \varphi_{D1,x1} < \gamma_{th}\right) \\
&= \Pr\left(\varphi_{D1,x2} < \gamma_{th}\right)\Pr\left(\varphi_{D1,x1} < \gamma_{th}\right).
\end{aligned}
\tag{13}
$$

where $\gamma_{th} = 2^{2R} - 1$ is threshold SNR.

Lemma 1: We call $X = |h_S|^2, Y = |h_D|^2$ are random variables with average gains as Ω_{SR}, Ω_{RD} The outage probability of two-variable function can be expreesed by

$$
OP = Pr\left(Y < \frac{a}{bX - c}\right) = 1 - \exp\left(-\frac{c}{b\Omega_{SR}}\right)QK_1(Q),
\tag{14}
$$

where $K_1(.)$ denotes as Bessel second kind , $Q = \sqrt{\dfrac{4a}{b\Omega_{SR}\Omega_{RD}}}$.

Proof: See in appendix.

Applying interesting results obtained in Lemma 1, it can be performed several outage events as:

$$
\Pr\left(\varphi_{D1,x1} < \gamma_{th}\right) = 1 - \exp\left(-\frac{B}{v_1\Omega_{SR}}\right)\sqrt{\frac{4A}{v_1\Omega_{SR}\Omega_{RD}}}K_1\left(\sqrt{\frac{4A}{v_1\Omega_{SR}\Omega_{RD}}}\right),
\tag{15}
$$

where $B = \eta\alpha\beta(1-\beta)\sigma^2\gamma_{th}$, $A = (1-\alpha)(1-\beta)\sigma^2\gamma_0$, $v_1 = \eta\alpha\beta(1-\beta)P_S a_1^2$.

$$
\Pr\left(\gamma_{D1,x2} < \gamma_{th}\right) = 1 - \exp\left(-\frac{B}{v_2\Omega_{SR}}\right)\sqrt{\frac{4A}{v_2\Omega_{SR}\Omega_{RD}}}K_1\left(\sqrt{\frac{4A}{v_2\Omega_{SR}\Omega_{RD}}}\right),
\tag{16}
$$

where $v_2 = \eta\alpha\beta(1-\beta)P_S\left(a_2^2 - \gamma_{th}a_1^2\right)$.

3.2. SCHEME II

In similar way, we compute outage event as:

$$
OP_{SCHEME2} = 1 - \Pr\left(|h_S|^2 > \varepsilon_1, |h_{D1}|^2 > \frac{b\varepsilon_1}{\sigma^2\left(|h_S|^2 - \varepsilon_1\right)}, |h_{D1}|^2 > \frac{b\varepsilon_2}{\sigma^2\left(|h_S|^2 - \varepsilon_2\right)}\right),
\tag{17}
$$

where $\varepsilon_1 = \dfrac{\gamma_{th1}}{\rho a_1^2 - \rho a_2^2\gamma_{th1}}$, $\varepsilon_2 = \dfrac{a\gamma_{th2}}{\rho a_2^2}$

Then, the outage probability in SCHEME II can be expressed by:

$$OP_{SCHEME2} = 1 - \Pr\left(|h_S|^2 > \varepsilon_1, |h_{D1}|^2 > \frac{b\varepsilon}{\sigma^2\left(|h_S|^2 - \varepsilon\right)} \right)$$

$$= 1 - \exp\left(-\frac{\varepsilon_1}{\Omega_{SR}}\right) \sqrt{\frac{4\left(b\varepsilon + \sigma^2\varepsilon\right)}{\Omega_{SR}\Omega_{RD}\sigma^2}} K_1\left(\sqrt{\frac{4\left(b\varepsilon + \sigma^2\varepsilon\right)}{\Omega_{SR}\Omega_{RD}\sigma^2}} \right),$$

(18)

where $\varepsilon = \max\left\{\varepsilon_1, \varepsilon_2\right\}$

3.3. Throughput

$$\tau_\ell = \left(1 - OP_\ell\right)R,$$

(19)

where $\ell \in \left\{Scheme\ I, Scheme\ II\right\}$

4. Numerical Results

       Unless otherwise stated, we set the source transmission rate, $R = 1$ (bits/sec/Hz) in the delay limited transmission mode, energy harvesting efficiency, $\eta = 1$, source transmission power, $P_S = 1$ Joules/sec. For simplicity, similar noise variances at the relay and the destination nodes are assumed, i.e., different kinds of noise variance is set as $\sigma^2 = 1$. The mean values, Ω_{SR}, Ω_{RD} of the exponential random variables $|h_S|^2, |h_D|^2$, respectively, are set to 1. NOMA has power allocation factors are $a_1 = 0.2, a_2 = 0.8$.

       Figure 2 plot the outage probability for cooperative NOMA with different power allocation factors for AF relaying, where energy harvesting fractions contribute to change outage performance shown as different curves. Observing the Figure 2, one can conclude that compared among three cases of EH-NOMA, the proposed scheme with higher time aware energy harvesting allocation for energy harvesting can realize worse outage performance r. Furthermore, Figure 2 manifest that EH-NOMA can remarkably enhance the outage performance at high transmit power at source P_S. More importantly, the analytical curves match very well with Monte-Carlo results.
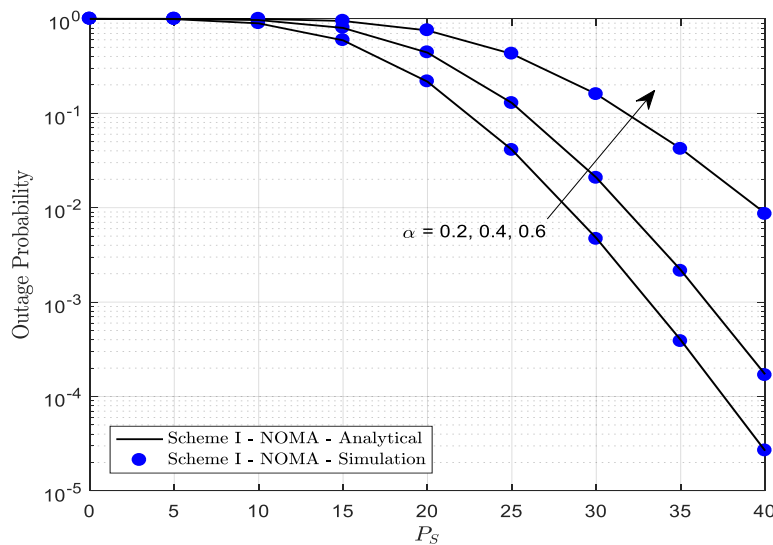

Figure 2. Outage performance versus transmit power at source at fixed power-aware energy harvesting $\beta = 0.1$
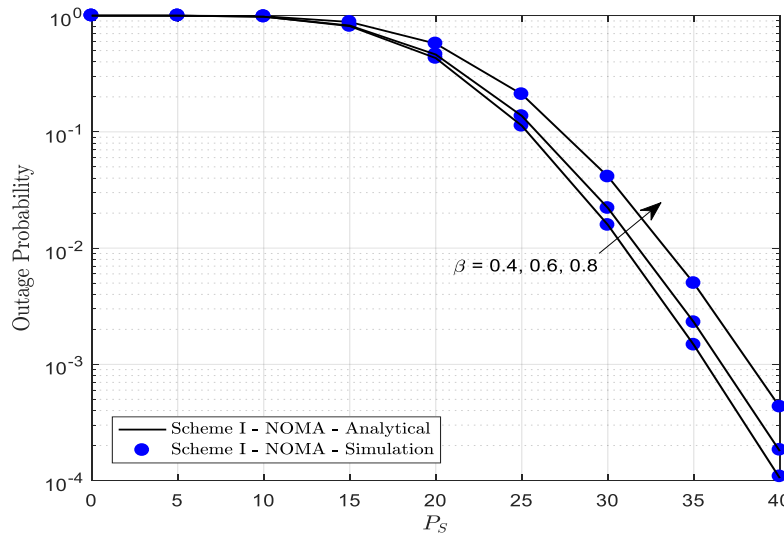
Figure 3. Outage performance versus transmit power at source at fixed time-aware energy harvesting $\alpha = 0.1$

In Scheme I, Figure 3 plots the outage probability for cooperative NOMA in case of fixed time aware energy harvesting factor is set and varying power aware energy harvesting factor in TPSR protocol depoying in Scheme I. As can be seen clearly that the proposed scheme with higher power aware energy harvesting allocation for energy harvesting can realize worse outage performance. Similarly, Figure 3 confirmed that that EH-NOMA can provide the best outage performance as reasonable selection of P_S .

As can be seen in Figure 4, it shows the optimal throughput versus changing variance noise term in EH- NOMA in case of changing transmit power at source. It is noted that throughput can be shown as $(1 - OP_{Scheme1})R_0(1 - \alpha)$ corresponding fixed rate R_0 . As can be seen clearly that the proposed scheme with higher transmit power ($P_S = 3(J/s)$ can realize better throughput performance due to more energy for signal processing. It is noted that noise term contributes to lower throughput, especially at high noise -20 to -10dB
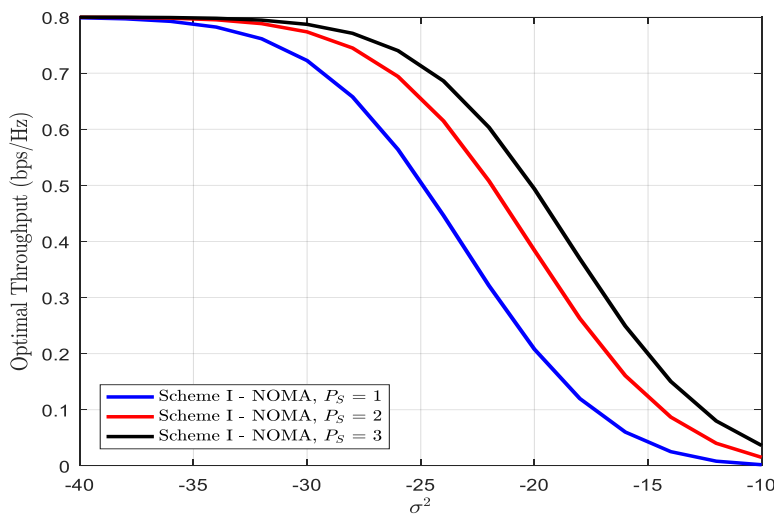

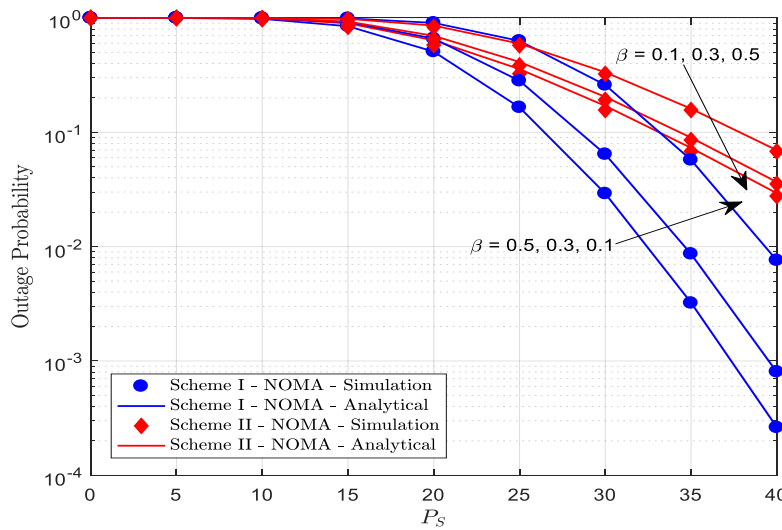Figure 4. The throughput versus noise as varying transmit power at source

Figure 5. Outage comparison the proposed system in two schemes

In Figure 5, we compare the outage performance for EH-NOMA in two schemes by using different gain factor in AF mode and different percentage of harvested energy. It can be observed from Figure 5 that Scheme I can achieve better outage performance than that in Scheme II. Furthermore, we can also see that the outage performance of NOMA is enhanced significantly with high transmit power at source. In addition, Figure 5 also demonstrates that energy harvesting remain operation of relay where has signal processing and outage performance at acceptable as reasonable selection of related parameters as in simulation result.
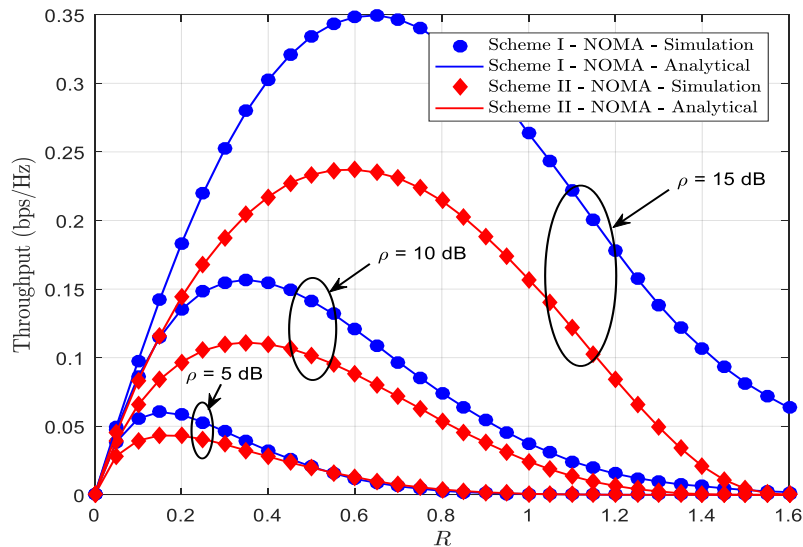

Figure 6. Impact of bit rates on the throughput

It is can be found optimal throughput at specific bit rate. As dervided expressions of outage behavior, bit rate is factor impacting outage performance as in Figure 6. In particular, the throughput in Scheme I is better than that in Scheme II at 3 cases of SNR value of the base

station. The highest throughput can be observed at about 0.62 for Scheme I and 0.6 for Scheme II corresponding with $\rho = 15\,(dB)$.

5. Conclusion

In this paper, we have proposed two kinds of AF modes as presented in two schemes. With regard to EH-NOMA relaying schemes, we have derived asymptotic analytical expressions for outage probability. These results provide guidline to design practical NOMA system. The proposed cooperative NOMA schemes not only achieve reasonable performance but also yield better outage performance at specific scenarios. In addition, compared to different power allocation fractions, the proposed NOMA schemes can further improve the outage probability at appropriate energy harvesting policy.

Appendix
PROOF OF LEMMA 1:

It is required that $b|h_S|^2 - c \neq 0$. In this case, outage probability denoted as OP can be given in two cases below:

In case of $|h_S|^2 < c/b$ then:

$$OP = Pr\left(|h_D|^2 < \frac{a}{b|h_S|^2 - c} \right). \tag{A1}$$

In case of $|h_S|^2 > c/b$ then:

$$OP = Pr\left(|h_D|^2 > \frac{a}{b|h_S|^2 - c} \right) = 1. \tag{A2}$$

Therefore, OP can be formulated as

$$OP = \int_0^{c/b} Pr\left(|h_D|^2 > \frac{a}{b\gamma - c} \right) f_{|h_S|^2}(\gamma)d\gamma$$
$$+ \int_{c/b}^{\infty} Pr\left(|h_D|^2 < \frac{a}{b\gamma - c} \right) f_{|h_S|^2}(\gamma)d\gamma \tag{A3}$$
$$= \int_0^{c/b} f_{|h_S|^2}(\gamma)d\gamma + \int_{c/b}^{\infty} \left(1 - \exp\left\{ -\frac{\theta}{(bx - c)\Omega_{RD}} \right\} \right) f_{|h_S|^2}(\gamma)d\gamma,$$

where Ω_{SR} and Ω_{RD} are respectively average gain of channels $|h_S|^2$ and $|h_D|^2$. It can be solved the intergral by applying characterization together with as

i) $f_{|h_S|^2}(\gamma) = \frac{1}{\Omega_{SR}} e^{-\gamma/\Omega_{SR}}$ is (PDF) of random variables $|h_S|^2$,

ii) $F_{|h_D|^2}(\gamma) = Pr\left(|h_D|^2 < \gamma\right) = 1 - e^{-\gamma/\Omega_{RD}}$ stands for (CDF) of random variable $|h_D|^2$.

As a result, OP can be expressed as

$$OP = 1 - \frac{1}{\Omega_{SR}} \int_{c/b}^{\infty} \exp\left\{-\frac{\gamma}{\Omega_{SR}} - \frac{\theta}{(b\gamma - c)\Omega_{RD}}\right\} d\gamma. \tag{A4}$$

It can be changed to new variable $\mu = b\gamma - c$. As a result, outage probability can be computed completely.

Applying interesting results obtained in [2,3], it can be performed outage event as below:

$$OP = Pr\left(|h_D|^2 < \frac{a}{b|h_S|^2 - c}\right) = 1 - \exp\left(-\frac{c}{b\Omega_{SR}}\right) Q K_1(Q), \tag{A5}$$

Where $Q = \sqrt{\dfrac{4a}{b\Omega_{SR}\Omega_{RD}}}$, $K_1(.)$ denotes as Bessel second kind.

This completes the proof.

References
[1] XX Nguyen, Dinh-Thuan Do. *Optimal Power Allocation and Throughput Performance of Full-Duplex DF Relaying Networks with Wireless Power Transfer-Aware Channel.* EURASIP Journal on Wireless Communications and Networking. 2017: 152.
[2] Dinh Thuan Do. *Power Switching Protocol for Two-way Relaying Network under Hardware Impairments.* Radioengineering. 2015; 24(3): 765-771.
[3] AA Nasir, X Zhou, S Durrani, RA Kennedy. *Relaying protocols for wireless energy harvesting and information processing.* IEEE Transactions on Wireless Communications. 2013; 12(7): 3622–3636.
[4] XX Nguyen, Dinh Thuan Do. Maximum Harvested Energy Policy in Full-Duplex Relaying Networks with SWIPT. *International Journal of Communication Systems (Wiley).* 2017.
[5] TL Nguyen, Dinh Thuan Do. *A new look at AF two-way relaying networks: energy harvesting architecture and impact of co-channel interference.* Annals of Telecommunications. 2017; 72: 669-678.
[6] Dinh Thuan Do, HS Nguyen. *A Tractable Approach to Analyze the Energy-Aware Two-way Relaying Networks in Presence of Co-channel Interference.* EURASIP Journal on Wireless Communications and Networking. 2016: 271.
[7] KT Nguyen, Dinh-Thuan Do, XX Nguyen, NT Nguyen, DH Ha. *Wireless information and power transfer for full duplex relaying networks: performance analysis.* Proc. of Recent Advances in Electrical Engineering and Related Sciences (AETA 2015), HCMC, Vietnam. 2015; 53-62.
[8] Y Saito, A Benjebbour, Y Kishiyama, T Nakamura. *System level performance evaluation of downlink non-orthogonal multiple access (NOMA).* Proc. IEEE 24th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC). 2013: 611–615.
[9] 3GPP Technical Report 36.859. *Study on Downlink Multiuser Superposition Transmission (MUST).* For LTE (Release 13). 2015.
[10] Z Ding, M Peng, HV Poor. *Cooperative non-orthogonal multiple access in 5G systems.* IEEE Communication Letter. 2015; 19(8): 1462-1465.
[11] JB Kim, IH Lee. *Non-orthogonal multiple access in coordinated direct and relay transmission.* IEEE Communication Letter. 2015; 19(11): 2037-2040.
[12] Z Zhang, Z Ma, M Xiao, Z Ding, P Fan. *Full-duplex device-to-device aided cooperative non-orthogonal multiple access.* IEEE Vehicular Technology Society. 2016; 66(5): 4467-4471.
[13] JB Kim, IH Lee. *Capacity analysis of cooperative relaying systems using non-orthogonal multiple access.* IEEE Communication Letter. 2015; 19(11): 1949-1952.
[14] S Arunmozhi, G Nagarajan. Performance of Full-Duplex One-Way and Two-Way Cooperative Relaying Networks. *Indonesian Journal of Electrical Engineering and Computer Science.* 2018; 9(2): 526-538.
[15] DT Do. Optimal Energy Har vesting Scheme for Power Beacon-Assisted Wireless-Powered Networks. *Indonesian Journal of Electrical Engineering and Computer Science.* 2017; 7(3): 802-808.

[16] F Obite, KM Yusof, J Din. *A Mathematical Approach for Hidden Node Problem in Cognitive Radio Networks. Telkomnika (Telecommunication, Computing, Electronics and Control).* 2017; 15(3): 1127-1136.

[17] Dinh Thuan Do, HS Nguyen. *A Tractable Approach to Analyze the Energy-Aware Two-way Relaying Networks in Presence of Co-channel Interference*. EURASIP Journal on Wireless Communications and Networking. 2016: 271.