Research article

Outage and throughput analysis of power-beacon assisted nonlinear energy harvesting NOMA multi-user relay system over Nakagami-\(m\) fading channels

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**A R T I C L E   I N F O**

Keywords:
Electrical engineering
Algebra
Statistics
Probability theory
Signal processing
Wireless network
Communication system
Non-orthogonal multiple access
Power beacon
Nonlinear energy harvesting
Successive interference cancellation
Outage probability
Throughput

**A B S T R A C T**

This paper considers a non-orthogonal multiple access (NOMA) multi-user relay system where both source and relay harvest the energy from a power beacon (PB) equipped with multiple antennas and use this harvested energy to transmit signals to several users. Realistic nonlinear energy harvesting models are applied, and time switching protocols are adopted at source and relay. We successfully derive the exact closed-form expressions of the outage probability and throughput of the system over Nakagami-\(m\) fading channels. Then, we use Monte-Carlo simulations to validate the correctness of these derived mathematical expressions. Numerical results show that a higher saturated power threshold of the nonlinear energy harvester results in lower outage probability and higher throughput. Moreover, the optimal time switching ratio that maximizes the throughput is smaller than the optimal time switching ratio that minimizes the outage probability.

**1. Introduction**

Electronic devices may not be powered by electricity mesh in some circumstances. Therefore, using radio frequency (RF) energy harvesting (EH) to support the operations of low-power communication devices in small-cell and sensor networks is considered as a promising research direction \([1, 2]\). On the other hand, due to the increase in the amount of data traffic, the number of wireless devices and communications in wireless networks, there is increasing spectrum demand. Fortunately, the non-orthogonal multiple access (NOMA) was proposed to replace the traditional multiple access thanks to its capability of high efficient spectrum usage \([3, 4]\). Therefore, combining SWIPT with NOMA can solve the problem of energy and spectrum efficiency in the fifth-generation (5G) and beyond wireless networks \([5, 6, 7]\).

The RF-EH can be classified into three different types: simultaneous wireless information and power transfer (SWIPT), ambient RF source-assisted wireless power supply, and dedicated power beacon (PB)-assisted wireless power supply. Among these RF-EH techniques, the advantages of PB-assisted wireless power supply is fully controllable, providing various applications with high quality-of-service (QoS) requirements \([8, 9]\). The PB-assisted wireless-powered communication was investigated in \([10]\). However, the authors only considered the linear EH model and studied the optimal power allocation in a point-to-point conventional wireless communication system instead of deriving the closed-form expressions of the outage probability and throughput of a NOMA relay system. Non-linear (NL)-EH point-to-point cognitive radio systems were considered in \([11]\) and \([12]\). The authors studied the resource optimization problem and the transmission power minimization problem, respectively.

With regard to the research works on EH-NOMA systems in the literature, the authors in \([13]\) formulated a power optimization problem to maximize the energy efficiency of a NOMA-based cloud radio access network. Simulation results indicated that their proposed

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https://doi.org/10.1016/j.heliyon.2020.e05440
Received 6 August 2020; Received in revised form 3 October 2020; Accepted 2 November 2020

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NOMA scheme could obtain higher energy efficiency and throughput than the orthogonal multiple-access (OMA) method. Joint power allocation and splitting control for SWIPT-enabled NOMA systems was proposed in [14], with an aim to optimize the total transmission rate and harvested energy simultaneously while satisfying the minimum rate and the harvested energy requirements of each user. Numerical results demonstrated that significant performance gain over the traditional rate maximization scheme could be achieved. The authors of [15] mathematically evaluated the impact of partial relay selection on the performance of a downlink EH-NOMA relay system. Notably, they found that the undecodable probability and ergodic capacity were significantly influenced by the efficiency of successive interference cancellation (SIC) and the number of relays. The application of SWIPT to NOMA networks with spatial randomly located users was investigated in [16]. It was shown that the opportunistic use of node locations for user selection could result in low outage probability and provide much better throughput compared to the random selection scheme. In [17], the authors considered a cooperative NOMA system where a source communicates with two users through an EH relay. They proposed two types of NOMA power allocation policies, i.e., NOMA with fixed power allocation (F-NOMA) and cognitive radio inspired NOMA (CR-NOMA), and investigated the impacts of these two power allocation policies on the considered cooperative SWIPT-NOMA system. It was indicated that the two proposed NOMA schemes could effectively reduce the outage probability while realizing the same diversity gain. In [18], the SWIPT-enable relay exploited the RF energy supplied by the two NOMA user groups to recharge itself. Meanwhile, in [19], the source was powered by an external source, whereas the relay employs power splitting SWIPT-based EH to harvest the energy from the source before transmitting signals to two users. As mentioned earlier, the EH techniques considered in [18] and [19] were SWIPT. Furthermore, linear EH models were used at the relays.

Unlike previous works that considered only linear EH-NOMA systems, the papers [11] and [12] investigated the point-to-point EH-NOMA systems with nonlinear EH at only secondary user or both primary user and secondary user. Moreover, the power was transferred from a primary base station (PBS) or a cognitive base station (CBS). The most related work to our paper is [20]. However, the authors considered the information source harvests the energy from the power source over Rayleigh fading channels by using the non-linear energy harvester. Therefore, in this paper, we propose and analyze a power-domain NOMA system where source and relay harvest the energy from multi-antenna power beacon by using non-linear EH over Nakagami–m fading channels. Moreover, instead of studying the resource allocation problem for sum rate maximization, we derive the closed-form expressions of the system’s outage probability and throughput.

The rest of this paper is organized as follows. Section 2 describes the system model of the considered PB-assisted NEH-NOMA multi-user relay system. Section 3 presents the detailed derivations of the exact closed-form expression of the outage probability and capacity used to analyze the performance of the considered system. Numerical results and discussions are given in Section 4. Finally, Section 5 concludes the paper.

2. System model

The system considered in this paper comprises a source (S), a relay (R), and N users (Dn, n ∈ [1,...,N]) as illustrated in Fig. 1. R employs decode-and-forward (DF) protocol and operates in half-duplex (HD) mode to forward signals from S to Dn. It is assumed that Dn uses fixed power supply while S and R harvest the RF energy transmitted from K antennas of a PBS.

Let us denote \( \sqrt{d_1^\beta} \) as the large-scale fading with \( d_1 \) being the distance between the endpoints of these links and \( \beta \) is the path loss coefficient; \( f_{\ell,k} \) (\( \ell \in [1,2] \), \( k \in [1,...,K] \)) and \( h_1 \) as the small-scale fading coefficients of PB–S, PB–R, and S–R links, respectively. Since RF-EH wireless networks often involve in short-range communications, the channel coefficients \( f_{1,k} = f_{1,k} \sqrt{d_1^\beta} \), \( f_{2,k} = f_{2,k} \sqrt{d_1^\beta} \) and \( h_1 = h_1 \sqrt{d_1^\beta} \) follow Nakagami distributions, i.e., \( f_{1,k} \sim G(m_1, \frac{m_1}{\Gamma(1)} \), \( f_{2,k} \sim G(m_2, \frac{m_2}{\Gamma(1)} \), and \( h_1 \sim G(m_1, \frac{m_1}{\Gamma(1)} \), respectively, as the large-scale fading and small-scale fading coefficients of K – Dn channel, where \( d_n \) represents the distance between R and Dn. \( g_n = g_n \sqrt{d_n^\beta} \) also follow Nakagami distribution, i.e., \( g_n \sim G(m_n, \frac{m_n}{\Gamma(1)} \), where \( \Omega_{Dn} = E[|g_n|^2] \) and \( n \in [1,...,N] \). Similar to [20], it is assumed that \( d_1 > d_2, ..., > d_N \). Thus, the channel gains are in an ascending order, i.e., \( 0 < |g_1|^2 < ..., < |g_N|^2 \).

In this system, S and R use time switching (TS) protocol to harvest the RF energy from the PB. Notably, within a transmission block time \( T \), the first time duration \( aT \), \( 0 \leq a < 1 \), is used to harvest the RF energy from PB and the remaining time duration \((1-a)T\) is used to transmit signals.

3. Performance analysis

We employ the maximal ratio transmission (MRT) scheme at the PB to improve the amount of harvested energy at S and R. Specially, for the same transmission power of the PB, the total transmission power is equally divided and then assigned to all antennas in the case of using MRT scheme. Meanwhile, the total transmission power is assigned to one selected antenna in the case of using transmit antenna selection (TAS) scheme. Thanks to the diversity gain of MRT schemes, the end-to-end signal-to-noise ratios (SNRs) of PB – S and PB – R channels are better than that of TAS scheme. As the result, the amount of received energy at S and R is higher.

Because of the usage of MRT scheme, the elements of channel vector \( f_{1,k} \) are distributed (i.i.d) [21], i.e.,

\[
|g_{1,k}|^2(a) = \left( \frac{m_p}{\Omega_1} \right) K m_k \exp \left( -\frac{m_p a}{\Omega_1} \right). \tag{1}
\]

The signal vector transmitted by PB with a size of \( K \times 1 \) is expressed as

\[
X = w_{x_{\ell}} s_{x_{\ell}}, \tag{2}
\]

where \( w_{x_{\ell}} \), \( \| w_{x_{\ell}} \|^2 = 1 \), refers to the beamforming vectors from PB to S and R, \( s_{x_{\ell}} \) is the symbol with \( \| s_{x_{\ell}} \|^2 = 1 \).

It is easy to observe that the optimal beamforming vector is given by [22]
\[ w_r = \|f_r\|/\|f_s\|. \]  

Then, the signals received at S and R in the EH phase are, respectively, presented as [23, 24]

\[ y_s = \sqrt{P_b} f_s + w_s, \]

\[ y_r = \sqrt{P_b} f_r + w_r, \]

where \( w_s \sim \mathcal{CN}(0, \sigma_s^2) \) and \( w_r \sim \mathcal{CN}(0, \sigma_r^2) \) are the additive white Gaussian noises (AWGNs) at S and R, respectively, \( \sigma_s^2 = E\{w_s^2\} \) is the variance of AWGN with \( x \in \{S, R\} \), \( P_b \) is the transmission power of PB, and \( E\{x^2\} = 1 \).

In practice, the output power of an energy harvester reaches a constant maximum value, which depends on the nonlinear EH circuit components such as inductors, capacitors, and diodes [23]. The nonlinear EH model’s characteristic can be modeled by the relationship between the input power and the output power of an energy harvester. Similar to [25, 26], a nonlinear EH model is also considered in this paper to reflect the operations of realistic systems. As a result, the transmission power of S and R can be given by

\begin{align*}
P_s &= \sum_{j=1}^{m_1} \frac{m_1 P_{th} \|f_j\|^2}{m_1 P_{th} + \|f_s\|^2}, \quad P_s \|f_s\|^2 \leq P_{th}, \\
P_k &= \sum_{j=1}^{m_1} \frac{m_1 P_{th} \|f_j\|^2}{m_1 P_{th} + \|f_s\|^2}, \quad P_k \|f_s\|^2 > P_{th},
\end{align*}

where \( P_{th} \) is the saturation power threshold and \( \eta, \; 0 < \eta < 1 \), is the energy conversion efficiency.

As shown in Fig. 2, when the transmission power of PB is greater than 100 W, the output power of the energy receiver is saturated. The distances from PB to EH nodes (S and R) significantly influence the amount of harvested power. In summary, the harvested power in the case of nonlinear EH cannot exceed a saturated value. This feature is contrary to linear EH, where the harvested power always increases with the transmission power of PB.

Next, S and R use all harvested energy to transmit signals to R and \( D_n \), respectively. Therefore, the signals received at R and \( D_n \) are expressed as

\[ \begin{align*}
y_r &= h_1 \sqrt{\alpha_k} P_k x_s + h_1 \sum_{j=1}^{m_1} \sqrt{\alpha_k} P_k x_j + w_r, \\
y_{D_n} &= h_2 \sqrt{\alpha_k} P_k x_s + h_2 \sum_{j=1}^{m_1} \sqrt{\alpha_k} P_k x_j + w_{D_n},
\end{align*} \]

From (7) and (8), the SINRs of S − R and R − \( D_n \) links in the case of nonlinear EH are, respectively, given by

\[ \psi_{\text{S−R}}^{\text{lin}} = \begin{cases} \frac{a_{\text{S−R}} P_k \|f_s\|^2}{a_{\text{S−R}} P_k \|f_s\|^2 + s_{\text{S−R}}}, & \text{if } P_k \|f_s\|^2 \leq P_{th} \\ \frac{a_{\text{S−R}} P_k \|f_s\|^2}{a_{\text{S−R}} P_k \|f_s\|^2 + s_{\text{S−R}}}, & \text{if } P_k \|f_s\|^2 > P_{th}. \end{cases} \]

\[ \psi_{\text{R−D_n}}^{\text{lin}} = \begin{cases} \frac{a_{\text{R−D_n}} P_k \|f_s\|^2}{a_{\text{R−D_n}} P_k \|f_s\|^2 + s_{\text{R−D_n}}}, & \text{if } P_k \|f_s\|^2 \leq P_{th} \\ \frac{a_{\text{R−D_n}} P_k \|f_s\|^2}{a_{\text{R−D_n}} P_k \|f_s\|^2 + s_{\text{R−D_n}}}, & \text{if } P_k \|f_s\|^2 > P_{th}. \end{cases} \]

where \( a_{\text{S−R}} \) is the power allocation coefficient for \( D_n \). We have assumed the channel gains are ascend order, i.e., \( 0 < |g_{\text{S−R}}|^2 < \ldots < |g_{\text{S−R}}| \). Following the principle of power domain NOMA, thus, \( a_1 > a_2 \ldots > a_N \) and \( \sum_{j=1}^{N} a_j = 1, \; \bar{a}_j = \sum_{i=j}^{N} a_i \), and \( \kappa = \frac{a_{\text{S−R}}}{a_{\text{S−R}}} \).

Let \( \text{OP} = \text{Pr}(\gamma_{\text{S−R}} < \gamma_{\text{R−D_n}}) \) be the outage probability (OP) of the system, where \( \gamma_{\text{S−R}} = \min(\psi_{\text{S−R}}^{\text{lin}}, \psi_{\text{R−D_n}}^{\text{lin}}) \), \( \gamma_{\text{R−D_n}} = 2^{x/n-1} - 1 \) with \( x \) is the threshold data rate of \( D_n \). When the events \( \gamma_{\text{S−R}} < \gamma_{\text{R−D_n}} \) and \( \gamma_{\text{S−R}} < \gamma_{\text{R−D_n}} \) occur, it means that R cannot decode the signal of D_n and D_n cannot decode the signal of S or its own signal. Thus, the OP of D_n is calculated as

\[ \text{OP}_n = 1 - \text{Pr}(\gamma_{\text{S−R}} < \gamma_{\text{R−D_n}}) \text{Pr}(\gamma_{\text{S−R}} < \gamma_{\text{R−D_n}}). \]

In the case that \( j \neq N \), we denote \( \bar{\theta}_j = \max(\gamma_{\text{S−R}}, \gamma_{\text{R−D_n}}, \ldots \gamma_{\text{R−D_n}}) \). Then, the OP of \( D_n \) can be expressed as

\[ \text{OP}_n = 1 - \text{Pr}(\psi_{\text{S−R}}^{\text{lin}} > \bar{\theta}_j) \text{Pr}(\psi_{\text{R−D_n}}^{\text{lin}} > \bar{\theta}_j). \]

The closed-form expressions of \( \Omega_1 \) and \( \Omega_2 \) are, respectively, given in (13) and (14). Detailed derivations of these equations are provided in the Appendix.
where \( \chi = \frac{\gamma_1}{\gamma_{th} - \gamma_1} \), \( \Gamma(\cdot, \cdot) \) is incomplete Gamma function, and \( K_n(\cdot) \) is the \( n \)th order modified Bessel function of the second kind [27].

It is worth noticing that the condition \( a_n > \theta^* \sum_{i=1}^{N} a_i \) should be satisfied to ensure \( \chi > 0 \). On the other hand, this condition indicates that SIC is performed from a high-power signal to a low-power signal. Otherwise, \( OP = 1 \), i.e., disconnected communication system.

From the OP expression, the throughput of each user in the system is calculated as

\[
\tau = \frac{(1-\alpha)r_n}{2}(1-OP_n).
\]

(15)

4. Numerical results

This section, the analysis and Monte-Carlo simulation results of the OP and throughput of the considered PB-assisted NL-EH-NOMA multi-user relay system in various evaluating scenarios are provided. PB is equipped with two antennas while S, R, and D\(_1\) have only one antenna. There are three users in the considered system, denoted as D\(_1\), D\(_2\), and D\(_3\). The threshold data transmission rates of all users are equal, i.e., \( r_1 = r_2 = r_3 = 1 \) b/s/Hz. The average channel gains are set as \( \Omega_1 = \Omega_2 = 1 \), \( \Omega_4 = \Omega_{D1} = 1 \), \( \Omega_{D2} = 2 \), and \( \Omega_{D3} = 4 \). The power allocation coefficient for D\(_1\) is \( a_n = (N-n+1)/\mu \) where \( \mu \) is selected so that \( \sum_{i=1}^{N} a_i = 1 \).

Fig. 3 plots the OP of D\(_1\) versus the average SNR in dB for different saturated power threshold \( P_{th} \). We can see that the OPs for all cases of \( P_{th} \) decreases as the SNR increases. Also, smaller \( P_{th} \) results in a higher outage floor. It is because small \( P_{th} \) makes the amount of harvested energy at S and R low, leading to high OP. Another feature is that, when \( P_{th} \) is small, there is a significant gap between the OPs of linear and nonlinear EH-NOMA systems. However, as \( P_{th} \) increases, this gap is reduced because higher \( P_{th} \) means nonlinear EH gradually becomes linear EH.

Fig. 4 depicts the OP of each user versus the average in dB for two settings of \( m \), i.e., \( m_1 = m_2 = m_3 = m_4 = 1.5 \) and 2.5. As observed in Fig. 4, the OPs of all users decrease as the SNR increases and reach different outage floors when the SNR exceeds certain values. In particular, larger \( m \) results in a higher outage floor. The reason for this feature is that the saturated power threshold \( P_{th} \) of nonlinear energy harvester closely influences the transmission power of S and R.

Fig. 5 and Fig. 6 show the OP and throughput of D\(_1\) versus the time switching ratio \( \alpha \) for different \( P_{th} \), respectively. As observed from Fig. 5, the OP remarkably reduces as \( \alpha \) gets higher, then sharply increases to

1 These values are based on the IEEE 802.11a/g standards.
1 when $a$ is larger than a certain value, e.g., $a = 0.8$ for $P_{th} = 15$ dB. In contrast, the throughput in Fig. 6 rapidly increases with $a$ and then quickly decreases to 0 when $a$ exceeds a specific value, e.g., $a = 0.1$ for $P_{th} = 15$ dB. In other words, there exist different optimal values of $a$ that minimizes the OP and maximizes the throughput. Moreover, the $a$ at which the OP is the smallest increases with $P_{th}$. In contrast, the $a$ at which the throughput is highest decreases when $P_{th}$ increases. The reason behind this feature is that the OP is affected by the harvested power, while the throughput is influenced by the coherent time of the wireless channel.

5. Conclusion

In this paper, we have investigated a NOMA relay system where the single-antenna source and relay are equipped with nonlinear energy harvesters to receive the energy from a multiple-antenna power beacon by using TS protocol. Source and relay then utilize all harvested energy to transmit signals to several destinations. We derived the closed-form expressions of the OP and throughput of the considered PB-assisted NL-EH-NOMA multi-user relay system over Nakagami-$m$ fading channels and used Monte-Carlo simulations to validate these derived expressions. Numerical results show that a higher saturated power threshold of the nonlinear energy harvester results in the lower OP and higher throughput. The OP reaches outage floor as the average SNR exceeds a specific value. This outage floor is lower when the nonlinear energy harvester’s saturated power threshold is larger, and the fading is more severe. Additionally, the optimal time switching ratio that maximizes the throughput is smaller than the optimal time switching ratio that minimizes the outage probability.

Declarations

Author contribution statement

Tran Manh Hoang: Conceived and designed the experiments; Performed the experiments; Wrote the paper.
Ba Cao Nguyen & Tran Thanh Trung: Performed the experiments; Analyzed and interpreted the data.
Le The Dung: Contributed reagents, materials, analysis tools or data; Wrote the paper.

Funding statement

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

Supplementary content related to this article has been published online at https://doi.org/10.1016/j.helyon.2020.e05440.

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