Throughput analysis of non-orthogonal multiple access and orthogonal multiple access assisted wireless energy harvesting K-hop relaying networks

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ABSTRACT

This study introduces the non-orthogonal multiple access (NOMA) technique into the wireless energy harvesting K-hop relay network to increase throughput. The relays have no dedicated energy source and thus depend on energy harvested by wireless from a power beacon (PB). Recently, NOMA has been promoted as a technology with the potential to enhance connectivity, reduce latency, increase fairness amongst users, and raise spectral effectiveness compared to orthogonal multiple access (OMA) technology. For performance considerations, we derive exact throughput expressions for NOMA and OMA-assisted multi-hop relaying and compare the performance between the two. The obtained results are validated via Monte Carlo simulations.

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1. INTRODUCTION

Wireless energy harvesting enables the development of new devices for internet-of-medical things (IoMT), wireless sensor networks (WSNs), infrastructure and environmental monitoring and surveillance where battery-powered devices would be unsuitable [1]–[3]. In addition, energy harvesting enables energy sufficiency and lifetime operation for devices placed within building materials and the human body [1]. The potential application for wireless energy harvesting is relay networks, where the source transmit power during the uplink functions as an arbitrary variable in wireless powered communication network (WPCN) because of the intrinsic power transmission. Due to the dramatic increase of battery-powered communication devices, the goal of extending their life is very important, and the highest throughput in the shortest amount of time, a good allocation of uplink and downlink times were calculated by [4], [5]. For example, in a wide-body area network (WBAN), or IoMT, the relays depend on a reliable and perpetual source of energy since battery replacement would be undesirable [4], [6]. There are various types of natural sources for harvesting, such as thermal, chemical, and vibration. In this paper, we consider harvesting energy from a power beacon (PB) based on the time switching protocol [7]–[9]. Hence, the source node transmits its data via relays, and every node makes use of the harvested PB energy for data transmission [10], [11]. As a result, K-hop relaying networks can provide line-of-sight (LoS) in obstruction filled environments such as indoor networks [12].

However, a fundamental problem faced by wireless energy harvesting multi-hop relaying network is the issue of throughput. Tian *et al.* [13] developed an optimal throughput broadcast algorithm to deal with the stochastic nature of the source and energy collection at the relays. In [14]–[16], a throughput algorithm is designed to acquire solutions to the optimal time and non-convex power distribution problem in wireless energy-harvesting cognitive radio networks. The authors in [17]–[19] investigated wireless powered communication networks assisted by non-orthogonal multiple access (NOMA), where signal is transmitted to a sink node, and the sink utilizes successive interference cancellation (SIC) to remove interference at its receivers.

NOMA is viewed as a viable candidate to increase connectivity and spectral effectiveness than traditional orthogonal multiple access (OMA) methods in emerging wireless networks by exploiting SIC and superposition coding to enable more user connectivity with no interference [20]–[22]. Internet of thing (IoT) security is a challenge due to limitations in connectivity, form factor, complexity, and power. Recently, many studies have been proposed for physical layer security (PLS) techniques in the fifth generation (5G); however, due to complex limitations, some of these solutions cannot be applied in IoT networks. NOMA is considered a viable technology to solve latency and connectivity requirements in IoT [23]–[27]. In [28]–[31], the authors have applied a NOMA with implementation of signal processing on the downlink side. A nearby user can be a relay to transfer the signal to the far user by taking advantage of the benefits of full-duplex mode, allowing the relay to transmit and receive signals at the same time. For efficient data transmission, the shadowing and fading effects of the channels also play an important role [32]–[34]. Additionally, reconfigurable intelligent surfaces (RIS) is an emerging technology that is combined with multiple antennas-aided wireless systems with the presence of NOMA to the assistance improvement of far user performance [35], [36].

Motivated by the above ideas, we analyze a proposed wireless energy harvesting multi-hop decode and-forward relay network assisted NOMA. The main contributions of this study are i) compared with the system model and mathematical formula reported in [17], this paper proposes relays operating in half-duplex mode and ii) we derive exact throughput analytical expressions for NOMA assisted wireless energy harvesting multi-hop networks, as well as for the OMA case, and compare the throughput performance using simulation results. The closed-form throughput results are verified by Monte Carlo simulations.

The rest of this work is organized in the following way: section 2 describes the recommended system parameters. Then, in section 3, we derive the exact results of the throughput for the NOMA and OMA cases. We highlight the results in section 4, and give an important results summary in section 5.

2. SYSTEM MODEL

As shown in Figure 1, the source-T_0 transmits information to the destination-T_K through $K-1$ relays are said to be $T_1, T_2, \dots, T_{K-1}$. The transmitter T_K harvests energy from the PB to supply energy for its decode-and-forward (DF) actions, where $k = 0,1, \dots, K-1$. All nodes in our system have a single antenna. Therefore, K orthogonal time slots are used for information transmission.

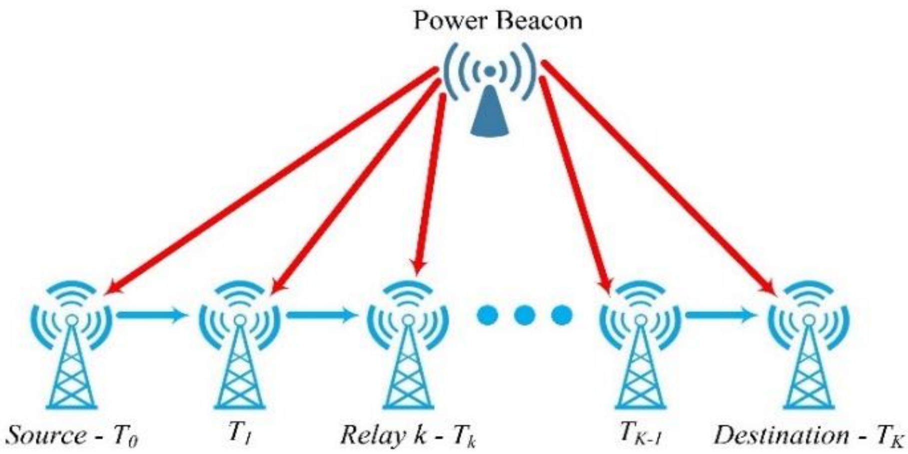

Figure 1. A K-hop DF relay network with energy collection from PB functionality

We define Q as the time for end-to-end transmission. Thus, the dedicated time slot for data transmission is $\tau = Q/K$. In addition, a portion of the time slot $\alpha\tau$ is dedicated for energy harvesting from the PB, and the remainder $(1-\alpha)\tau$ is used for decoding and forwarding operations, where $0<\alpha<1$ represents the block time portion. Thus, the harvest energy by T_K is written as [20].

$$\bar{E}_k = \eta\alpha\tau\bar{P}_P\bar{h}_{P_k} \tag{1}$$

where $(0\le\eta\le1)$ is the energy conversion efficiency, $\bar{P}_P$ is the power of PB transmitter, $\bar{h}_{P_k}$ represents the channel between PB and T_K.

From (1), the T_K transmitter power is obtained as (2) [37]:

$$\bar{P}_k = \frac{\bar{E}_k}{(1-\alpha)\tau} = \delta\bar{P}_P\bar{h}_{P_k} \tag{2}$$

where $\delta = \frac{\eta\alpha}{1-\alpha}$.

Remark 1: To simplify our calculations, we assume that the energy harvesting operates on different frequencies to the data transmission process, thus, preventing interference at the relay receivers.

We consider that in the k-th time slot, node T_{k-1} transmits data to node T_K, where $k = 1,\ldots,K$. To improve throughput, the relay T_{k-1} uses superposition coding to combine N signals to produce a superimposed signal expressed as (3).

$$\bar{x} = \sum_{n=1}^{N}\sqrt{a_n\bar{P}_{k-1}\bar{x}_n} \tag{3}$$

with for $n = 1,2,\ldots,N$; a_n represents the power allocation coefficients, $\sum_{n=1}^{N}a_n = 1$ and $a_1 > a_2 >\ldots> a_N$; $\bar{x}_n$ is the transmitted signal.

Remark 2: Traditionally, OMA has been the backbone of K-hop relaying resulting in a data rate of $1/K$. Thus, by superposing N signals, our proposed scheme's data rate is N/K.

Assuming perfect successive interference cancellation (pSIC) [21], [22], [38], [39], the T_K the transmit signal-to-noise ratio (SNR) for decoding $\bar{x}_n$ under hardware impairments can be written as (4) [40]:

$$\bar{\psi}_k^n = \begin{cases} \dfrac{a_n\bar{P}_{k-1}\bar{h}_{D_k}}{\kappa^2\bar{P}_{k-1}\bar{h}_{D_k} + \sum_{i=n+1}^{N}a_i\bar{P}_{k-1}\bar{h}_{D_k} + N_0} & \textbf{if } n<N \\ \dfrac{a_N\bar{P}_{k-1}\bar{h}_{D_k}}{\kappa^2\bar{P}_k\bar{h}_{D_k} + N_0} & \textbf{if } n=N \end{cases} \tag{4}$$

where $\bar{h}_{D_k}$ is the channel gain between T_{k-1} and T_K, K^2 is the combined hardware impairment [41]–[43], and N_0 is the additive white gaussian noise (AWGN). Substituting (2) into (5) yields.

$$\bar{\Psi}_k^n = \begin{cases} \dfrac{\rho a_n\delta\bar{h}_{P_{k-1}}\bar{h}_{D_k}}{\left(\kappa^2 + \sum_{i=n+1}^{N}a_i\right)\rho\delta\bar{h}_{P_{k-1}}\bar{h}_{D_k} + 1} & \textbf{if } n<N \\ \dfrac{\rho a_N\delta\bar{h}_{P_{k-1}}\bar{h}_{D_k}}{\kappa^2\rho\delta\bar{h}_{P_{k-1}}\bar{h}_{D_k} + 1} & \textbf{if } n=N \end{cases} \tag{5}$$

Where $\rho = \bar{P}_P / N_0$ is the transmit SNR.

Furthermore, the instantaneous channel capacity of $\bar{x}_n$ is obtained as (6).

$$\bar{C}_k^n = (1-\alpha)\tau\, log_2\,(1+\bar{\psi}_k^n). \tag{6}$$

The channel capacity of $\bar{x}_n$ with DF relaying as (7).

$$\bar{C}^{n}_{\text{e2e}} = \min_{k=1,2,\dots,K}(\bar{C}^{n}_{k}). \tag{7}$$

Finally, we can define the throughput similar to [4], [14] as (8).

$$T_{\text{NOMA}} = (1-\alpha)\tau\bar{\gamma}_{th}\sum_{n=1}^{N} Pr(\bar{C}^{n}_{\text{e2e}} \geq \bar{\gamma}_{th}) \tag{8}$$

where $\bar{\gamma}_{th}$ is desired target rate.

We also consider the K-hop relaying with OMA. Here, T_{k-1} uses power $\bar{P}_{k-1}$ to transmit one signal to T_K. Therefore, the throughput becomes [44]:

$$T_{\text{OMA}} = (1-\alpha)\tau\gamma_{\text{th}}\, Pr\left(\bar{C}^{\text{OMA}}_{\text{e2e}} \geq \bar{\gamma}_{th}\right) \tag{9}$$

where

$$\bar{C}^{\text{OMA}}_{\text{e2e}} = \min_{k=1,2,\dots,K}\left((1-\alpha)\tau\log_2\left(1+\frac{\rho\delta\bar{h}_{P_{k-1}}\bar{h}_{D_k}}{\kappa^2\rho\delta\bar{h}_{P_{k-1}}\bar{h}_{D_k}+1}\right)\right). \tag{10}$$

3. THROUGHPUT ECALUATION

3.1. Nakagami-m fading channel model

We assume the system channels follow Nakagami-m fading also that the channel gains $\bar{h}_{P_k}$ and $\bar{h}_{D_k}$ are exponential random variables (RVs). We define Ω_{P_k} and Ω_{D_k} as the RVs channel parameters. Thus, cumulative distribution functions (CDFs) of the $\bar{h}_{P_k}$ and $\bar{h}_{D_k}$can be written by [45], respectively as in (11) and (12).

$$F_{\bar{h}_{P_k}}(x) = 1 - e^{-\frac{x}{\beta_{P_k}}}\sum_{n=0}^{m_{P_k}-1}\frac{x^n}{n!\beta_{P_k}^{n}}n \tag{11}$$

$$F_{\bar{h}_{D_k}}(x) = 1 - e^{-\frac{x}{\beta_{D_k}}}\sum_{n=0}^{m_{D_k}-1}\frac{x^n}{n!\beta_{D_k}^{n}}. \tag{12}$$

Therefore, the probability density functions (PDF) of $\bar{h}_{P_k}$ and $\bar{h}_{D_k}$are obtained as [46]:

$$f_{\bar{h}_{P_k}}(x) = \frac{x^{m_{P_k}-1}}{\Gamma\left(m_{P_k}\right)\beta_{P_k}^{m_{P_k}}}e^{-\frac{x}{\beta_{P_k}}} \tag{13}$$

$$f_{\bar{h}_{D_k}}(x) = \frac{x^{m_{D_k}-1}}{\Gamma\left(m_{D_k}\right)\beta_{D_k}^{m_{D_k}}}e^{-\frac{x}{\beta_{D_k}}} \tag{14}$$

where $\beta_z \triangleq \frac{\Omega_z}{m_z}, z \in (P_k; D_k)$.

Taking the path loss into account, the channel parameters Ω_{P_k} and Ω_{D_k} can be modeled as (15) [47]:

$$\Omega_{P_k} = d_{P_k}^{-\varepsilon}, \Omega_{D_k} = d_{D_k}^{-\varepsilon} \tag{15}$$

where d_{P_k} and d_{D_k} are the distances of $Pb \to T_k$ and $T_k \to T_{k+1}$, respectively, the path-loss exponent is denoted by ε, Ω_{P_k} and m_z denote the mean and the integer fading factor.

3.2. NOMA throughput analysis

Firstly, we calculate the probability $Pr(\bar{C}^{n}_{e2e} \geq \gamma_{th})$. Taking $n < N$ and combining (5) to (7), we obtain (16).

$$Pr(\bar{C}^{n}_{\text{e2e}} \geq \gamma_{th}) = \prod_{k=1}^{K} Pr(\bar{C}^{n}_{k} \geq \gamma_{th}) = \prod_{k=1}^{K} Pr\left(\frac{\rho a_n\delta\bar{h}_{P_{k-1}}\bar{h}_{D_k}}{\left(\kappa^2+\sum_{i=n+1}^{N}a_i\right)\rho\delta\bar{h}_{P_{k-1}}\bar{h}_{D_k}+1} \geq \theta\right) \tag{16}$$

where $\theta = 2^{\frac{\gamma_{th}}{(1-\alpha)\tau}} - 1$ is the SINR threshold. It is obvious from (16) that if $\alpha_n - \theta(\kappa^2 + \sum_{i=n+1}^{N} \alpha_i) \le 0$ then $Pr(\bar{C}_{e2e}^{n} \ge \gamma_{th}) = 0$, and if $\alpha_n - \theta(\kappa^2 + \sum_{i=n+1}^{N} \alpha_i) > 0$, (16) becomes:

$$Pr(\bar{C}_{\mathrm{e2e}}^{n} \ge \gamma_{th}) = \prod_{k=1}^{K} Pr\left(\bar{h}_{P_{k-1}} \bar{h}_{D_k} \ge \bar{\sigma}_n\right) \tag{17}$$

where

$$\bar{\sigma}_n = \frac{\theta}{[\alpha_n - (\kappa^2 + \sum_{i=n+1}^{N} \alpha_i)\theta]\rho\delta}. \tag{18}$$

Remark 3: The transmit power ratio α_n must be carefully designed so that the conditions, i.e., $\alpha_n - \theta(\kappa^2 + \sum_{i=n+1}^{N} \alpha_i) > 0$, are satisfied.

Now, the probability $Pr\left(\bar{h}_{P_{k-1}} \bar{h}_{D_k} \ge \bar{\sigma}_n\right)$ can be formulated by (19).

$$Pr\left(\bar{h}_{P_{k-1}} \bar{h}_{D_k} \ge \bar{\sigma}_n\right) = \int_0^{+\infty} \left(1 - F_{\bar{h}_{P_{k-1}}}\left(\frac{\bar{\sigma}_n}{x}\right)\right) f_{\bar{h}_{D_k}}(x) dx. \tag{19}$$

Putting (11) to (14) in (19), and then using [48], (3.471.9), we get (20).

$$\begin{aligned} Pr(\bar{C}_{\mathrm{e2e}}^{n} \ge \gamma_{th}) &= \prod_{k=1}^{K} \left[\int_0^{\infty} \left(1 - F_{P_{k-1}}\left(\frac{\bar{\sigma}_n}{x}\right)\right) f_{D_k}(x) dx\right] \\ &= \prod_{k=1}^{K} \left[\sum_{l=0}^{m_{P_{k-1}}-1} \frac{\bar{\sigma}_n^l}{l!\, \beta_{P_{k-1}}^l \Gamma(m_{D_k}) \beta_{D_k}^{m_{D_k}}} \times \int_0^{\infty} e^{-\frac{\bar{\sigma}_n}{\beta_{P_{k-1}} x} - \frac{x}{\beta_{D_k}}} x^{m_{D_k} - l - 1} dx\right] \\ &= \prod_{k=1}^{K} \left[\sum_{l=0}^{m_{P_{k-1}}-1} \frac{2\rho_n^l}{l!\beta_{P_{k-1}}^l \Gamma(m_{D_k}) \beta_{D_k}^{m_{D_k}}} \times \left(\frac{\beta_{D_k}\bar{\sigma}_n}{\beta_{P_{k-1}}}\right)^{\frac{m_{D_k}-l}{2}} K_{m_{D_k}-l}\left(2\sqrt{\frac{\bar{\sigma}_n}{\beta_{P_{k-1}}\beta_{D_k}}}\right)\right] \end{aligned} \tag{20}$$

Where $K_u(.)$ stands for the u^{th} order of the modified Bessel function of the second kind [48], (3.471.9). Similarly, when $n = N$ we get (21).

$$Pr(\bar{C}_{\mathrm{e2e}}^{N} \ge \gamma_{th}) = \prod_{k=1}^{K} \left[\sum_{l=0}^{m_{P_{k-1}}-1} \frac{2\bar{\sigma}_N^l}{l!\beta_{P_{k-1}}^l \Gamma(m_{D_k}) \beta_{D_k}^{m_{D_k}}} \times \left(\frac{\beta_{D_k}\bar{\sigma}_N}{\beta_{P_{k-1}}}\right)^{\frac{m_{D_k}-l}{2}} K_{m_{D_k}-l}\left(2\sqrt{\frac{\bar{\sigma}_N}{\beta_{P_{k-1}}\beta_{D_k}}}\right)\right] \tag{21}$$

Where $\bar{\sigma}_N = \frac{\theta}{(\alpha_N - \kappa^2\theta)\rho\delta}$. Inserting (8), (20) and (21) together, an exact closed-form formula of T_{NOMA} is acquired as (22).

$$\begin{aligned} T_{\mathrm{NOMA}} &= (1-\alpha)\tau\gamma_{th} \\ &\times \left\{\sum_{n=1}^{N} \prod_{k=1}^{K} \left[\sum_{l=0}^{m_{P_{k-1}}-1} \frac{2\bar{\sigma}_N^l}{l!\beta_{P_{k-1}}^l \Gamma(m_{D_k}) \beta_{D_k}^{m_{D_k}}} \times \left(\frac{\beta_{D_k}\bar{\sigma}_N}{\beta_{P_{k-1}}}\right)^{\frac{m_{D_k}-l}{2}} K_{m_{D_k}-l}\left(2\sqrt{\frac{\bar{\sigma}_N}{\beta_{P_{k-1}}\beta_{D_k}}}\right)\right]\right\}. \end{aligned} \tag{22}$$

3.3. OMA throughput analysis

For multi-hop relaying using OMA, we get

$$\begin{aligned} Pr\left(\bar{C}_{\mathrm{e2e}}^{\mathrm{OMA}} \ge \gamma_{th}\right) &= \prod_{k=1}^{K} Pr\left(\bar{h}_{P_{k-1}} \bar{h}_{D_k} \ge \bar{\xi}\right) \\ &= \prod_{k=1}^{K} \left[\sum_{l=0}^{m_{P_{k-1}}-1} \frac{2\bar{\xi}^l}{l!\beta_{P_{k-1}}^l \Gamma(m_{D_k}) \beta_{D_k}^{m_{D_k}}} \times \left(\frac{\beta_{D_k}\bar{\xi}}{\beta_{P_{k-1}}}\right)^{\frac{m_{D_k}-l}{2}} K_{m_{D_k}-l}\left(2\sqrt{\frac{\bar{\xi}}{\beta_{P_{k-1}}\beta_{D_k}}}\right)\right] \end{aligned} \tag{23}$$

where $\bar{\xi} = \frac{\theta}{(1-\kappa^2\theta)\rho\delta}$. From (23), the throughput T_{NOMA} is expressed as (24).

$$T_{\text{OMA}} = (1-\alpha)\tau\gamma_{th} \times \prod_{k=1}^{K}\left[\sum_{l=0}^{m_{P_{k-1}}-1} \frac{2\bar{\xi}^{l}}{l!\beta_{P_{k-1}}^{l}\Gamma(m_{D_k})\beta_{D_k}^{m_{D_k}}} \times \left(\frac{\beta_{D_k}\bar{\xi}}{\beta_{P_{k-1}}}\right)^{\frac{m_{D_k}-l}{2}} K_{m_{D_k}-l}\left(2\sqrt{\frac{\bar{\xi}}{\beta_{P_{k-1}}\beta_{D_k}}}\right)\right]. \quad (24)$$

4. MUMERICAL RESULTS

Here, we address the main parameters of Monte Carlo simulation. The source node is located at the origin (0, 0) and the destination at (1, 0), thus the distance between the source and the destination node is 1. Then, the coordinates of the relay T_k and the power beacon PB are (k / K, 0) and (0.5, 0.5), respectively, with $k=1, 2, ..., K-1$. We set $m_{P_{k-1}} = m_{P_k} = m_{D_{k-1}} = m_{D_k} = m = 2$. Three NOMA schemes are considered as follows. In scheme I, we consider $a_1=0.85$, $a_2=0.15$, and $N=2$; in scheme II, we set $a_1=0.85$, $a_2=0.12$, $a_3=0.03$, and $N=3$; and in scheme III, the parameters are $a_n \in \{0.85, 0.12, 0.025, 0.005\}$, with $n=1,2,3,4$, and $N=4$. Monte-Carlo results are averaged over 10^7 independent channel executions. Specifically, Table 1 shows the main parameters.

Table 1. System parameters used in the throughput evaluation

System Parameters	Values
The aggregate impairment level	$\kappa^2 = 0.01$
Targeted data rate	$\bar{\gamma}_{th} = 0.1$
The total transmission time	$Q = 1$
Pass loss exponent	$\varepsilon = 3$
The energy conversion efficiency	$\eta = 1$
The fraction of the block time	$\alpha = 0.1$

Observe the relationship between throughput and transmit SNR shown in Figure 2 with parameters $m = 2, \kappa^2 = 0.01, \alpha = 0.1$, and $K = 3$, we found different throughput performance curves depending on N, the number of superposed signals, with NOMA-analytical $N = 4$ has the best performance. Compared to OMA, NOMA outperforms OMA significantly in Figure 2.

Observe the relationship between throughput and transmit SNR with parameters $\kappa^2 = 0.01$, $\alpha = 0.1$, and $K = 3$. We see different throughput performance curves depending on Nakagami-m fading parameter m, with NOMA-analytical $m = 3$ performing the best. Compared to OMA, NOMA outperforms OMA significantly in Figure 3. Furthermore, the throughput of OMA reaches a ceiling at transmitting SNR $\rho = 10\ dB$.

In Figures 4, and 5, we can see the continued trend of NOMA outperforming OMA. However, in Figure 4, we observe the throughput reduction by adding of K-hops. Also, in Figure 5, we notice that throughput decreases drastically beyond the optimal α. This highlights the importance of designing optimal time-switching protocols. All analytical curves match well with the Monte Carlo simulation results.

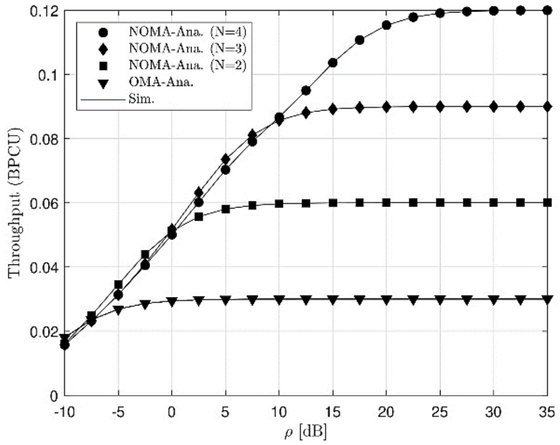

Figure 2. Throughput with $m = 2, \kappa^2 = 0.01$, $\alpha = 0.1$ and $K = 3$

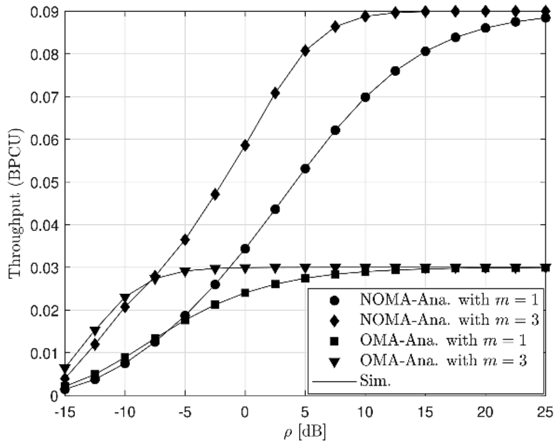

Figure 3. Throughput with $\kappa^2 = 0.01, \alpha = 0.1$ and $K = 3$

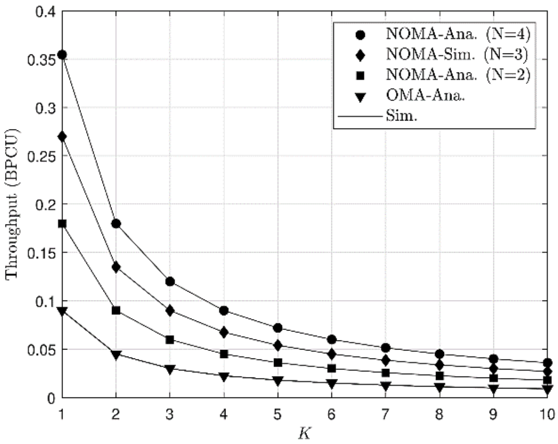

Figure 4. Throughput with $\kappa^2 = 0, m = 3$ and $\rho = 25\ dB$

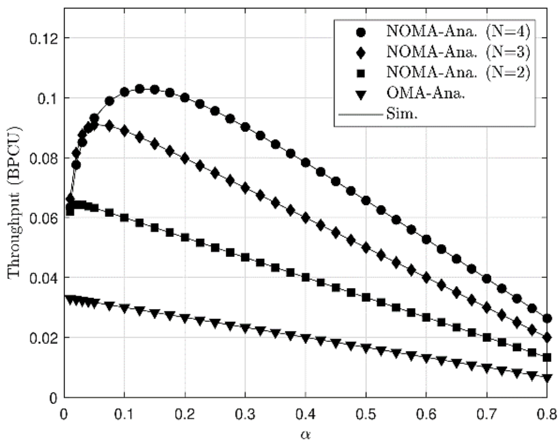

Figure 5. Throughput with $K = 3, \kappa^2 = 0$, $m = 3$ and $\rho = 10\ dB$

5. CONCLUSION

In this study, we provided a throughput analysis of NOMA assisted wireless energy harvesting multi-hop decode-and-forward network. We derived exact throughput expressions for the NOMA and OMA assistance. The results of simulation show that time switching and the number of relays play a significant role in throughput. We will consider a system that uses multiple power beacons in future work.

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