OUTAGE PROBABILITY OF DOWNLINK NOMA ENERGY HARVESTING FOR MULTIPLE USERS OVER RAYLEIGH FADING CHANNELS

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Abstract- In this paper, we propose down-link non-orthogonal multiple access (NOMA) networks for multiple users with energy harvesting (EH). Over Rayleigh fading channels, we derive the closed form expression for the system outage probability (OP). Monte Carlo simulation is utilized to verify the correctness of the analytics results confirming the advantage of the proposed networks. The effects of key system parameters such as time allocation coefficient, power allocation coefficient, and average signal-to-noise (SNR) on the system performance are also investigated.

Keywords: Index Terms-energy harvesting, non-orthogonal multiple access, power domain, Rayleigh fading channel, successive interference cancellation.

I. INTRODUCTION

From 1G to 5G, orthogonal multiple access (OMA) has been used to solve shared radio resource problems for multiple users. In simple receivers, the clear benefit of such orthogonal designs in the prevention of mutual interference among user equipment can lead to achieving high system performance. In beyond 5G systems, the data rate requirement of application types needs to be larger than 100 Gbps [1, 2]. Besides, a number of concurrently and massively connected devices under ultra-reliable constraints show that OMA schemes are not a suitable technology candidate for such beyond 5G systems. Therefore, recent attention has focused on the provision of non-orthogonal multiple access (NOMA) schemes, which are classified into two groups: power-domain NOMA and code-domain NOMA. NOMA is shown to have the potential to handle a massive number of connections while providing better user fairness and network capacity [3].

The energy supply for wireless devices beyond 5G systems is a challenge, especially for resource-limited wireless sensor networks, for example, drones and smartphones. These devices are small in size, battery-powered based, unwired for flexible mobility, and need to operate continuously without loss of power. As a result, the radio-frequency energy harvesting (EH) technique has become one of the technical solutions for addressing this power shortage issue [4, 5].

Applying radio-frequency EH in NOMA schemes has recently been examined in a few pieces of literature to enhance both energy and spectral efficiencies, for example [6] [7] [8] [9] [10] [11]. Under the scope of two destinations in the system, Hoang *et al.* [6] examined the outage performance of a NOMA system, where a source transmits data to two NOMA destinations with the help of a decode-and-forward (DF) relay node. Due to the limitation of energy supply, the relay uses EH via radio frequency to maintain the operation. To achieve maximal system throughput, the time used for harvesting energy at the relay was derived. Next, a system in which one of the destinations plays the relaying role for the other was proposed in [7]. To perform such a role as well as receive its own data, the relay is equipped with two antennas, whereas the other user has only one antenna. Both users use power-domain NOMA to receive data transmitted from the base station. The EH relay node harvests energy from the base station. Both outage probability and ergodic rates were derived in closed-form and the results showed that this system outperforms its counterparts. Different from [6], the EH-NOMA model in [8] applied EH via RF signals at both source node and relay node from a power beacon (PB) in a vehicle-to-vehicle Rayleigh fading network. The results have shown that two destinations could obtain the same performance capacity so that fairness was guaranteed. Within the scope of the multi-user problem, the outage probability of two kinds of users was derived from closed-form expressions in [9]. Under the NOMA scheme combined with the beamforming technique, each antenna at a base station can support a cluster of users. The energy harvesting technique is deployed by the strong user to relay the weak user's data. Furthermore, the system performance was investigated through the impact of imperfect self-interference and EH circuits. Recently, a solution for transmitting both power and user data at the same time on downlink channels was given through proposed resource allocation schemes [10]. The system architecture model in [10] can switch between two modes, which are orthogonal frequency division multiple access (OFDMA) and NOMA. The operating mode is chosen based on the quality of the channel state information estimation. Unlike [6], the number of mobile users is generalized to multiple users instead of two users. Besides,

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mobile users work under limited energy harvesting constraints and need the assistance of relay nodes. The system performance was evaluated through optimal algorithms for power allocation and subcarrier allocation for OFDMA/NOMA modes. Inspired by the idea of combining OMA and NOMA in [10], a proposed system under four scenarios was studied in [11]. In particular, NOMA is used with or without time division multiple access (TDMA) according to how passive user equipment operates. There are two kinds of user equipment (UE): passive UE and active UE. Specifically, passive UEs harvest energy from active UEs during their uplink transmission using NOMA. As concluded in [11], the NOMA-plus-TDMA system has a higher sum-throughput than the system using NOMA alone.

Motivated by the aforementioned works, we focus on deriving the outage probability of a NOMA system with the EH technique deployed at the source node in this paper. Specifically, our model is the same one in [12] but ours is combined with EH. Besides that, we also investigate the effect of the time allocation coefficient on the end user performance. By considering the Rayleigh fading channel, we derive an exact closed-form user outage probability, which is valid for multiple users. Matlab-based Monte Carlo simulation is performed to verify the correctness of the derivation approach and confirm the advantages of the proposed system.

The remainder of this paper is organized into sections as below. Section II presents the system model and solves the problems of cumulative distribution function (CDF) and probability density function (PDF) expressions of the user's signal-to-interference-noise rate (SINR). In Section III, we present the outage probability analysis of the system. In Section IV, numerical results under Monte Carlo simulations are performed to verify the analysis results. Last but not least, we conclude the paper and propose some future research directions in Section V.

II. SYSTEM MODEL

We consider a down-link NOMA network, where a base station (BS) communicates with M users (U_m) as shown in Fig. 1. We assume that BS is not equipped with the power source and must use energy harvested from a power beacon (PB). We further assume that all communication nodes, i.e., BS and U_m, are equipped with a single antenna.

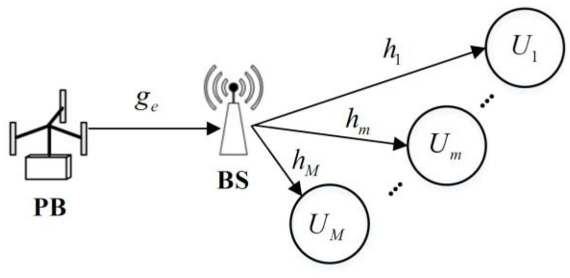

Figure 1: System model of downlink NOMA energy harvesting for multiple users.

We denote g_e and h_m as the channel coefficients between $\text{PB} \to \text{BS}$ and $\text{BS} \to U_m$, respectively. The process of transmitting energy and information between BS and U_m takes place in two time slots with the time duration, βT and $(1-\beta)T$, respectively, where β is the time allocation coefficient with $\beta \in (0,1)$ and T is the transmission time of a standard symbol in direct transmission mode [13, 14]. For optimal system performance, the value of β should be chosen properly [15, 16].

In the first time slot, PB provides energy to BS. For time duration of βT, the harvested energy at BS, E_{BS}, is given by [17-19]

$$E_{\text{BS}} = \varepsilon P_{\text{PB}} |g_e|^2 \beta T, \tag{1}$$

where P_{PB} is the transmit power of PB and ε is the energy harvest efficiency with $0 \le \varepsilon \le 1$.

In the second time slot of $(1-\beta)T$, the transmit power of BS is expressed as [20]

$$P_{\text{BS}} = \frac{\varepsilon P_{\text{PB}} |g_e|^2 \beta T}{(1-\beta)T} = \frac{\varepsilon P_{\text{PB}} |g_e|^2 \beta}{(1-\beta)}. \tag{2}$$

Using NOMA scheme [21, 22], BS will broadcast $\sum_{m=1}^{M} \sqrt{\alpha_m P_{\text{BS}}} s_m$ to all U_m, where s_m is the U_m data message and α_m is the power allocation coefficient, which must satisfy the condition of $\sum_{m=1}^{M} \alpha_m = 1$ [22, 23]. The received signal at U_m can be written by

$$\begin{aligned} y_m &= h_m \left(\sum_{m=1}^{M} \sqrt{\alpha_m P_{\text{BS}}} s_m \right) + n_m \\ &= h_m g_e \left(\sum_{m=1}^{M} \sqrt{\alpha_m \frac{\varepsilon P_{\text{PB}} \beta}{(1-\beta)}} s_m \right) + n_m, \end{aligned} \tag{3}$$

where n_m is complex additive white Gaussian noise (AWGN) at U_m with variance σ_m^2. Without losing generalization, we assume $\sigma_m^2 = \sigma^2, \forall m$.

For ease of analysis, we denote d_m as the distance between BS and U_m sorted as $d_M \le \ldots \le d_1$. Corresponingly, we also have channel coefficients sorted and power allocation coefficients sorted as $|h_M|^2 \ge \ldots \ge |h_1|^2$ and $\alpha_M \le \ldots \le \alpha_1$ since the distance between $\text{BS} \to U_m$ is inversely proportional to the channel coefficient and directly proportional to the power allocation coefficient [12].

At U_m, s_i with $i \le m$ can be detected and then be removed from awareness based on the signal strength in a successive manner, i.e., successive interference cancellation (SIC). SIC is a technique that was first proposed by Cover to decode the superposed signals on receivers in broadcast channels [24]. In particular, SIC can recover weaker signals while traditional techniques only can decode the strongest signal and treat the other signals as interference [25]. In particular, U_m will treat s_i with $i < m$ as noise. It also means that users will remove their farther message and treat their closer message as noise (based on signal strength). Therefore, the received SINR of U_m (except the M -th user) is given by

$$\gamma_m = \frac{\alpha_m |h_m|^2 |g_e|^2 \frac{\varepsilon P_{\mathrm{PB}}\beta}{(1-\beta)}}{|h_m|^2 \sum_{i=m+1}^{M} \alpha_i |g_e|^2 \frac{\varepsilon P_{\mathrm{PB}}\beta}{(1-\beta)} + \sigma^2} = \frac{\alpha_m |h_m|^2}{|h_m|^2 \sum_{i=m+1}^{M} \alpha_i + \frac{1}{|g_e|^2 \frac{\varepsilon\beta}{(1-\beta)}\rho}}, \quad (4)$$

where ρ is the average signal to noise ratio (SNR), i.e, $\rho = P_{\mathrm{PB}}/\sigma^2$.

Especially, U_M is the user, which is the closest one to BS. After removing the other users' messages by SIC, the received SNR at U_M (without interference), γ_M , is detemined as

$$\gamma_M = \alpha_M |h_M|^2 |g_e|^2 \frac{\varepsilon\beta}{(1-\beta)}\rho. \quad (5)$$

Considering independent and identically distributed Rayleigh-fading channels, all instantaneous channel gains, i.e., $|h_m|^2$ and $|g_e|^2$, follow exponential distributions with characteristic parameters λ_m and λ_e, respectively. The CDF and PDF of X with $X \in \left\{|h_m|^2, |g_e|^2\right\}$ are of the forms, respectively, as [16]

$$F_X(x) = 1 - \exp\left(-\lambda_{\tilde{X}} x\right),\ x \ge 0, \quad (6)$$

$$f_X(x) = \lambda_{\tilde{X}} \exp\left(-\lambda_{\tilde{X}} x\right),\ x \ge 0, \quad (7)$$

where $\lambda_{\tilde{X}} \in \{\lambda_m, \lambda_e\}$ represents the characteristic parameter with respect to the scheme X .

We are now in a position to derive the CDF of γ_m with $m = 1,\ldots,M$. It is noted from (4) and (5) that two cases of γ_m should be considered separately, i.e., Case 1: γ_m with $m = 1,\ldots,M-1$ and Case 2: γ_M . For the first case of γ_m, the CDF of γ_m is presented as

$$F_{\gamma_m}(\gamma) = \Pr\left(\gamma_m = \frac{\alpha_m |h_m|^2}{|h_m|^2 \sum_{i=m+1}^{M} \alpha_i + \frac{1}{|g_e|^2 \frac{\varepsilon\beta}{(1-\beta)}\rho}} < \gamma\right) = \Pr\left[|h_m|^2 < \frac{\gamma}{\left(\alpha_m - \gamma \sum_{i=m+1}^{M} \alpha_i\right)|g_e|^2 \frac{\varepsilon\beta}{(1-\beta)}\rho}\right]. \quad (8)$$

Observing (8), we can see that $|h_m|^2$ and $|g_e|^2$ appears in the left-hand side and the right-hand side of (8), respectively. Using the conditional probability for two random variables [26], (8) can be rewritten as

$$F_{\gamma_m}(\gamma) = \int_0^\infty F_{|h_m|^2}\left(\frac{\gamma}{\left(\alpha_m - \gamma \sum_{i=m+1}^{M} \alpha_i\right)\frac{\varepsilon\beta}{(1-\beta)}\rho x}\right) \times f_{|g_e|^2}(x)\,dx. \quad (9)$$

Substituting (6) and (7) into (9), we get

$$\begin{aligned} F_{\gamma_m}(\gamma) &= \int_0^\infty \left\{1 - \exp\left[-\frac{\lambda_m \gamma}{\left(\alpha_m - \gamma \sum_{i=m+1}^{M} \alpha_i\right)\frac{\varepsilon\beta}{(1-\beta)}\rho x}\right]\right\} \times \lambda_e \exp(-\lambda_e x)\,dx \\ &= \underbrace{\int_0^\infty \lambda_e \exp(-\lambda_e x)\,dx}_{\mathbf{I}_1} - \underbrace{\int_0^\infty \lambda_e \exp\left[-\frac{\lambda_m \gamma}{\left(\alpha_m - \gamma \sum_{i=m+1}^{M} \alpha_i\right)\frac{\varepsilon\beta}{(1-\beta)}\rho x} - \lambda_e x\right]dx}_{\mathbf{I}_2}. \end{aligned} \quad (10)$$

To obtain $F_{\gamma_m}(\gamma)$, we need to calculate $\mathbf{I}_1$ and $\mathbf{I}_2$. It's easy to regconize that

$$\mathbf{I_1} = \int_0^\infty \lambda_e \exp(-\lambda_e x)\,dx = 1. \quad (11)$$

For $\mathbf{I}_2$, we employ (3.324) in [27] to calculate for $\mathbf{I}_2$ as follows:

$$\int_0^\infty \exp\left(-\frac{\beta}{4x} - \gamma x\right)dx = \sqrt{\frac{\beta}{\gamma}} K_1\left(\sqrt{\beta\gamma}\right),\ \beta \ge 0, \gamma > 0 \quad (12)$$

where $K_1(\bullet)$ is the Bessel function of the first kind. As a result, $\mathbf{I}_2$ can be given by

$$\mathbf{I}_2 = \lambda_e \sqrt{\frac{4\lambda_m \gamma}{\left(\alpha_m - \gamma \sum_{i=m+1}^{M} \alpha_i\right)\frac{\varepsilon\beta}{(1-\beta)}\rho\lambda_e}} \times K_1\left(\sqrt{\frac{4\lambda_m \lambda_e \gamma}{\left(\alpha_m - \gamma \sum_{i=m+1}^{M} \alpha_i\right)\frac{\varepsilon\beta}{(1-\beta)}\rho}}\right). \quad (13)$$

Substituting $\mathbf{I}_1$ in (11) and $\mathbf{I}_2$ (13) into (10), we obtain the CDF of γ_m with $m = 1,\ldots,M-1$ as follows:

$$F_{\gamma_m}(\gamma) = 1 - \lambda_e \sqrt{\frac{4\lambda_m \gamma}{\left(\alpha_m - \gamma \sum_{i=m+1}^{M} \alpha_i\right)\frac{\varepsilon\beta}{(1-\beta)}\rho\lambda_e}} \times K_1\left(\sqrt{\frac{4\lambda_m \lambda_e \gamma}{\left(\alpha_m - \gamma \sum_{i=m+1}^{M} \alpha_i\right)\frac{\varepsilon\beta}{(1-\beta)}\rho}}\right). \quad (14)$$

For the second case of γ_M, the same derivation approach for γ_m can be used. From (5), the CDF of γ_M is obtained as

$$F_{\gamma_M}(\gamma) = 1 - \lambda_e \sqrt{\frac{4\lambda_M \gamma}{\alpha_M \frac{\varepsilon\beta}{(1-\beta)}\rho\lambda_e}} K_1\left(\sqrt{\frac{4\lambda_M \lambda_e \gamma}{\alpha_M \frac{\varepsilon\beta}{(1-\beta)}\rho}}\right). \quad (15)$$

III. PERFORMANCE ANALYSIS

Outage probability (OP) is defined as the probability that the signal to interference plus noise ratio (or signal to noise ratio) falls below a system given thrershold, γ_{th}. Mathematically, we can write the OP for U_m as follows:

$$\text{OP}_m = \Pr\left(\gamma_m < \gamma_{\text{th}}\right). \quad (16)$$

Since we have two different cases for γ_m, we also have two user outage probabilities. For the first case, using (14), we have the OP for U_m with $m = \overline{1, M-1}$ as follows:

$$\text{OP}_m = F_{\gamma_m}(\gamma_{\text{th}}) = 1 - \lambda_e \sqrt{\frac{4\lambda_m \gamma_{\text{th}}}{\left(\alpha_m - \gamma_{\text{th}} \sum_{i=m+1}^{M} \alpha_i\right)\frac{\varepsilon\beta}{(1-\beta)}\rho\lambda_e}} \times K_1\left(\sqrt{\frac{4\lambda_m \lambda_e \gamma_{\text{th}}}{\left(\alpha_m - \gamma_{\text{th}} \sum_{i=m+1}^{M} \alpha_i\right)\frac{\varepsilon\beta}{(1-\beta)}\rho}}\right). \quad (17)$$

Similarly, we have the closed-form expression of OP for the closest user U_M to the BS as

$$\text{OP}_M = F_{\gamma_M}(\gamma_{\text{th}}) = 1 - \lambda_e \sqrt{\frac{4\lambda_M \gamma_{\text{th}}}{\alpha_M \frac{\varepsilon\beta}{(1-\beta)}\rho\lambda_e}} K_1\left(\sqrt{\frac{4\lambda_M \lambda_e \gamma_{\text{th}}}{\alpha_M \frac{\varepsilon\beta}{(1-\beta)}\rho}}\right). \quad (18)$$

V. NUMERICAL RESULTS AND DICUSSION

In this section, we present the numerical results by utilizing Monte Carlo simulations to validate our theoretical results in Sect. III. For simulation, the system parameters are set as follows: the given threshold is 0.2, i.e., $\gamma_{\text{th}} = 0.2$, the energy harvest efficiency is 60%, i.e., $\varepsilon = 0.6$. For channel settings, we consider a two-dimensional plane, where PB, BS and U_m are located at coodinates (0,1), (0,0) and (x_m, y_m), respectively. It is required that coordinate of U_m (x_m, y_m) must be chosen to ensure the condition of $d_M \le \ldots \le d_1$. For channel pathloss model, we adopt the simplified path loss model, where the average channel power factor is modelled as $\lambda_{XY} = d_{XY}^{\eta}$, where d is the physical distance between node X and Y with $X, Y \in \{\text{PB}, \text{BS}, U_m\}$ and η is the path loss exponent whose value usually takes value in range of 2 to 6 [28]. Here, we choose $\eta = 3$ for the illustrative purpose. For each simulation point, 10^6 bits are used [29].

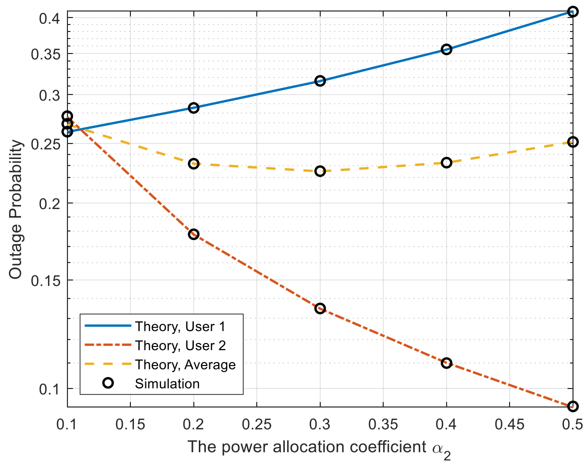

Figure 2: User OP versus power allocation coefficient.

In Figure 2, we plot the outage probability of end users as a function of the power allocation coefficient α_2 for two users, where $\rho = 5$ dB, $\beta = 0.5$, $U_1(0,1)$ and $U_2(0, 0.5)$. Since $\alpha_1 + \alpha_2 = 1$ and $d_2 \le d_1$, we consider α_2 in the range of 0.1 to 0.5 leading to $\alpha_2 \le \alpha_1$. It can be seen from Fig. 2 that increasing α_2 will increase the outage probability of User 1 but decrease the outage probability of User 2. To give insights, we plot the average curve of the outage probability of two users as a reference. It can be seen that there exists an optimal value of 0.3 for the average outage probability.

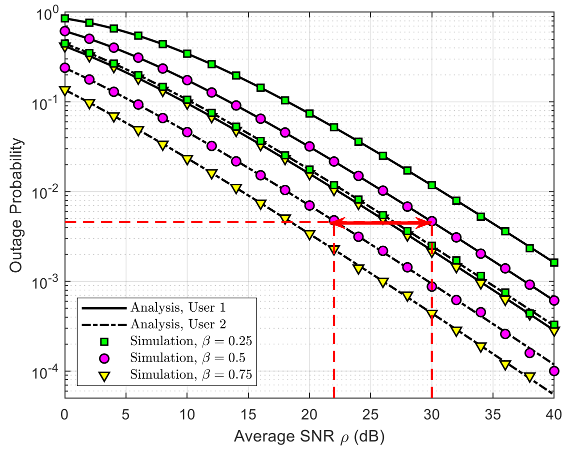

Figure 3: The OP as a function of the average SNR with the influence of the time allocation coefficient for M = 2.

In Fig. 3, we study the effect of time allocation coefficient on user outage probabilities with $(\alpha_1, \alpha_2) = (0.4, 0.6)$, $U_1(0,1)$ and $U_2(0,0.5)$. Three distinct cases of β are considered, i.e., Case 1: $\beta = 0.25$, Case 2: $\beta = 0.5$, and Case 3: $\beta = 0.75$. It can be observed that, for the same setting, outage probability for User 2 always outperforms outage probability for User 1. The performance gap between two users is quite significant, i.e., 8 dB, since User 1 is located more closed to BS than User 2. In addition, we can see that Case 3 outperforms Case 2, which, in turns, outperforms Case 1 confirming that increasing time allocation coefficient will improve the system performance.

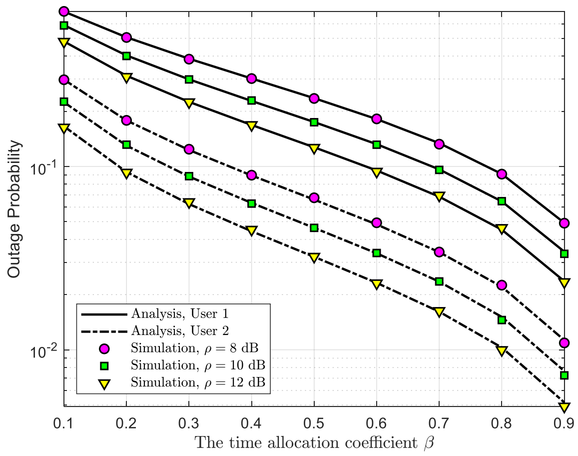

Figure 4: The OP of each user versus the time allocation coefficient with M = 2 users.

In Fig. 4, we refocus on effects of time allocation coefficient on user outage probability when ρ increases from 8 dB, 10 dB, and 12 dB. The coordination (0,1) and (0,0.5) corresponds with User 1 and User 2 as well. It is confirmed that increasing ρ will improve all user performance, as expected. In Fig. 4, it is further pointed out that all OPs decrease since the time allocation coefficient increases for all values of β under consideration.

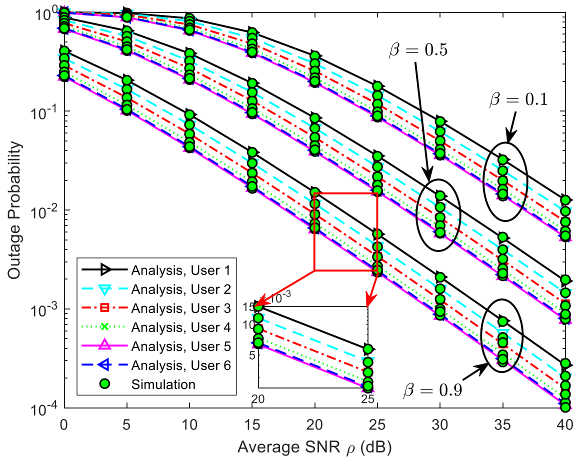

Figure 5: The OP at each user with M = 6 versus average SNRs .

From Fig. 2 to Fig. 4, we limit our numerical results in two end users. In Fig. 5, we consider the proposed network with 6 end users. The power allocation coefficients for six users should be calculated using the approach $\alpha_m = \frac{M-m+1}{\sum_{i=1}^{M} i}$ [16], resulting in $\alpha_1 = \frac{6}{21}$, $\alpha_2 = \frac{5}{21}$, $\alpha_3 = \frac{4}{21}$, $\alpha_4 = \frac{3}{21}$, $\alpha_5 = \frac{2}{21}$, and $\alpha_6 = \frac{1}{21}$. The coordinates of six users are $U_1(0,1)$, $U_2(0,0.9)$, $U_3(0,0.8)$, $U_4(0,0.7)$, $U_5(0,0.6)$, and $U_6(0,0.5)$, respectively. Three typical profiles of β are investigated including $\beta = 0.1$, $\beta = 0.5$, and $\beta = 0.9$. Again, it is confirmed that the system performance is significantly improved as aforementioned. For the same β, the end users, who are located closer to BS, give better performance. All simulation results are in the excellent agreement with the analysis results confirming the conrrectness of the proposed derivation approach.

V. CONCLUSION

In this paper, we have studied a down-link NOMA with EH strategy for multiple users. Here, NOMA is considered in the power-domain, whereas EH is investigated in the transmission mode of either energy transferring or information transferring at a certain time, where the process is conducted via two time slots. Over Rayleigh fading channels, we analyze and obtain the exact closed-form OP expression in the generic case with multiple users. Subsequently, the correctness of our analytical expressions is validated by Monte Carlo simulations as well as demonstrates the advantages of our proposed system model. The results have shown that the OP degradation holds for the average SNR increment, i.e., the quality of system is improved when increasing the PB transmit power. However, we must consider increasing SNR with just sufficient demand because it can cause interference to users of the network. Besides that, we study the beneficial impact of the time allocation coefficients on system performance. The results have revealed that better system performance can be achieved when assigning the longer energy harvesting duration compared to the information transferring time allocation. In addition, we also determine the optimal value for the power allocation coefficient for User 2 in the context of our assumed simulation parameters. However, we have not considered the closed-form expression for the power allocation coefficient optimization problem. This work can be studied in the future.

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REFERENCES

[1] W. Saad, M. Bennis, and M. Chen, "A Vision of 6G Wireless Systems: Applications, Trends, Technologies, and Open Research Problems," *IEEE Network,* vol. 34, no. 3, pp. 134-142, 2020, doi: 10.1109/MNET.001.1900287.

[2] N. N. Dao *et al.*, "Survey on Aerial Radio Access Networks: Toward a Comprehensive 6G Access Infrastructure," *IEEE Communications Surveys & Tutorials,* vol. 23, no. 2, pp. 1193-1225, 2021, doi: 10.1109/COMST.2021.3059644.

[3] L. Dai, B. Wang, Z. Ding, Z. Wang, S. Chen, and L. Hanzo, "A Survey of Non-Orthogonal Multiple Access for 5G," *IEEE Communications Surveys & Tutorials,* vol. 20, no. 3, pp. 2294-2323, 2018, doi: 10.1109/COMST.2018.2835558.

[4] M. L. Ku, W. Li, Y. Chen, and K. J. R. Liu, "Advances in Energy Harvesting Communications: Past, Present, and Future Challenges," *IEEE Communications Surveys & Tutorials,* vol. 18, no. 2, pp. 1384-1412, 2016, doi: 10.1109/COMST.2015.2497324.

[5] D. Ma, G. Lan, M. Hassan, W. Hu, and S. K. Das, "Sensing, Computing, and Communications for Energy Harvesting IoTs: A Survey," *IEEE Communications Surveys & Tutorials,* vol. 22, no. 2, pp. 1222-1250, 2020, doi: 10.1109/COMST.2019.2962526.

[6] T. M. Hoang, V. V. Son, N. C. Dinh, and P. T. Hiep, "Optimizing duration of energy harvesting for downlink NOMA full-duplex over Nakagami-m fading channel," *AEU - International Journal of Electronics and Communications,* vol. 95, pp. 199-206, 2018/10/01/ 2018, doi: https://doi.org/10.1016/j.aeue.2018.08.020.

[7] C. Guo, L. Zhao, C. Feng, Z. Ding, and H. Chen, "Energy Harvesting Enabled NOMA Systems With Full-Duplex Relaying," *IEEE Transactions on Vehicular Technology,* vol. 68, no. 7, pp. 7179-7183, 2019, doi: 10.1109/TVT.2019.2914508.

[8] B. C. Nguyen, T. M. Hoang, X. N. Pham, and P. T. Tran, "Performance Analysis of Energy Harvesting-Based Full-Duplex Decode-and-Forward Vehicle-to-Vehicle Relay Networks with Nonorthogonal Multiple Access," *Wireless Communications and Mobile Computing,* vol. 2019, p. 6097686, 2019/11/03 2019, doi: 10.1155/2019/6097686.

[9] Y. Alsaba, C. Y. Leow, and S. K. A. Rahim, "Full-Duplex Cooperative Non-Orthogonal Multiple Access With Beamforming and Energy Harvesting," *IEEE Access,* vol. 6, pp. 19726-19738, 2018, doi: 10.1109/ACCESS.2018.2823723.

[10] X. Zhang and F. Wang, "Resource Allocation for Wireless Power Transmission Over Full-Duplex OFDMA/NOMA Mobile Wireless Networks," *IEEE Journal on Selected Areas in Communications,* vol. 37, no. 2, pp. 327-344, 2019, doi: 10.1109/JSAC.2018.2872397.

[11] J. Wang, X. Kang, S. Sun, and Y. C. Liang, "Throughput Maximization for Peer-Assisted Wireless Powered IoT NOMA Networks," *IEEE Transactions on Wireless Communications,* vol. 19, no. 8, pp. 5278-5291, 2020, doi: 10.1109/TWC.2020.2991400.

[12] Z. Ding, Z. Yang, P. Fan, and H. V. Poor, "On the Performance of Non-Orthogonal Multiple Access in 5G Systems with Randomly Deployed Users," *IEEE Signal Processing Letters,* vol. 21, no. 12, pp. 1501-1505, 2014, doi: 10.1109/LSP.2014.2343971.

[13] V. N. Q. Bao and N. A. Tuấn, "Effect of imperfect CSI on wirelessly powered transfer incremental relaying networks," *Journal of Science and Technology on Information and Communications,* no. 3-4, pp. 48-57%V 1, 2017-04-11 2017. [Online]. Available: http://jstic.ptit.edu.vn/index.php/jstic/article/view/87.

[14] N. A. Tuan, V. N. Q. Bao, and L. Q. Cường, "A New Derivation Approach for Simultaneous Wireless Information and Power Transfer for MIMO Dual-Hop Relay Networks," *Journal of Science and Technology on Information and Communications,* no. 1, pp. 50-56%V 1, 2017-09-19 2017. [Online]. Available: http://jstic.ptit.edu.vn/index.php/jstic/article/view/155.

[15] I. Krikidis, Z. Gan, and B. Ottersten, "Harvest-use cooperative networks with half/full-duplex relaying," in *Proc. of the 2013 IEEEWireless Communications and Networking Conference (WCNC)*, 7-10 April 2013 2013, pp. 4256-4260, doi: 10.1109/WCNC.2013.6555261.

[16] T. T. Thanh and V. N. Quoc Bao, "Wirelessly Energy Harvesting DF Dual-hop Relaying Networks: Optimal Time Splitting Ratio and Performance Analysis," *Journal of Science and Technology: Issue on Information and Communications Technology,* no. 2, pp. 16-20%V 3, 2017-12-31 2017, doi: 10.31130/jst.2017.59.

[17] T. V. Nguyen, T. Do, V. N. Q. Bao, D. B. d. Costa, and B. An, "On the Performance of Multihop Cognitive Wireless Powered D2D Communications in WSNs," *IEEE Transactions on Vehicular Technology,* vol. 69, no. 3, pp. 2684-2699, 2020, doi: 10.1109/TVT.2020.2963841.

[18] P. M. Quang, T. T. Duy, and V. N. Q. Bao, "Performance Evaluation of Radio Frequency Energy Harvesting-Aided Multi-hop Cooperative Transmission Networks," in *2019 25th Asia-Pacific Conference on Communications (APCC)*, 6-8 Nov. 2019 2019, pp. 521-526, doi: 10.1109/APCC47188.2019.9026403.

[19] B. V. N. Quoc, T. H. Van, and K. Le, "Performance of Two-Way AF Relaying with Energy Harvesting over Nakagami-m Fading Channels," *IET Communications*. [Online]. Available: http://digital-library.theiet.org/content/journals/10.1049/iet-com.2018.5090

[20] N. A. Tuấn and V. N. Q. Bảo, "Phân Tích Hiệu Năng Hệ Thống Chuyển Tiếp Song Công Sử Dụng Công Nghệ Thu Thập Năng Lượng Từ Nguồn Phát," *Tạp Chí Khoa Học Và Công Nghệ, Đại Học Đà Nẵng* 2020.

[21] Y. Yu, H. Chen, Y. Li, Z. Ding, and B. Vucetic, "On the Performance of Non-Orthogonal Multiple Access in Short-Packet Communications," *IEEE Communications Letters,* vol. PP, no. 99, pp. 1-1, 2017, doi: 10.1109/LCOMM.2017.2786252.

[22] H. V. Hoa and V. N. Q. Bao, "Outage Performance of Cooperative Underlay Cognitive Radio with Non-Orthogonal Multiple Access," in *2019 25th Asia-*

Pacific Conference on Communications (APCC), 6-8 Nov. 2019 2019, pp. 527-532, doi: 10.1109/APCC47188.2019.9026514.

[23] H. V. Hoa, N. X. Quynh, and V. N. Q. Bao, "On the Performance of Non-Orthogonal Multiple Access schemes in Coordinated Direct with Partial Relay Selection," in *2018 International Conference on Advanced Technologies for Communications (ATC)*, 18-20 Oct. 2018 2018, pp. 337-343, doi: 10.1109/ATC.2018.8587530.

[24] T. Cover, "Broadcast channels," *IEEE Transactions on Information Theory*, vol. 18, no. 1, pp. 2-14, 1972, doi: 10.1109/TIT.1972.1054727.

[25] S. Sen, N. Santhapuri, R. R. Choudhury, and S. Nelakuditi, "Successive interference cancellation: a back-of-the-envelope perspective," presented at the Proceedings of the 9th ACM SIGCOMM Workshop on Hot Topics in Networks, Monterey, California, 2010. [Online]. Available: https://doi.org/10.1145/1868447.1868464.

[26] A. Papoulis and S. U. Pillai, *Probability, random variables, and stochastic processes*, 4th ed. Boston: McGraw-Hill, 2002, pp. x, 852 p.

[27] D. Zwillinger, *Table of integrals, series, and products*. Elsevier, 2014.

[28] A. Goldsmith, *Wireless communications*. Cambridge ; New York: Cambridge University Press, 2005, pp. xxviii, 644 p.

[29] V. N. Q. Bảo, *Mô phỏng hệ thống truyền thông*. Nhà Xuất Bản Khoa Học và Kỹ Thuật, 2020.

PHÂN TÍCH XÁC SUẤT DỪNG CỦA HỆ THỐNG ĐA TRUY NHẬP KHÔNG TRỰC GIAO (NOMA) ĐƯỜNG XUỐNG ĐA NGƯỜI DÙNG SỬ DỤNG KỸ THUẬT THU THẬP NĂNG LƯỢNG TRÊN KÊNH TRUYỀN FADING RAYLEIGH

Tóm tắt: Trong bài báo này, chúng tôi đề xuất mô hình đường xuống đa truy nhập không trực giao (NOMA) cho đa người dùng sử dụng kỹ thuật thu thập năng lượng. Chúng tôi đã phân tích xác suất dừng ở dạng đóng của các người dùng đầu cuối ở kênh truyền fading Rayleigg, và các kết quả này được kiểm chứng bằng mô phỏng Monte Carlo trên phần mềm Matlab, xác nhận ưu điểm của mô hình đề xuất. Ảnh hưởng của các tham số hệ thống quan trọng như hệ số phân bổ năng lượng, tỷ lệ tín hiệu trên nhiễu trung bình lên hiệu năng của hệ thống cũng được khảo sát.

Từ khóa- thu thập năng lượng, đa truy nhập không trực giao, miền công suất, kênh truyền fading Rayleigh, giải thuật loại can nhiễu tuần tự.

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