On The Performance of Non-Orthogonal Multiple Access Considering Random Waypoint Mobility Model

Mohannad Alzard[1], Saud Althunibat[2], and Nizar Zorba[1]

[1]*Department of Electrical Engineering, Qatar University, Doha, Qatar*
[2]*Department of Communications Engineering, Al-Hussein Bin Talal University, Ma'an, Jordan*
Emails: mohannad.elzard@qu.edu.qa, saud.althunibat@ahu.edu.jo, nizarz@qu.edu.qa

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***Abstract*—Non-Orthogonal Multiple Access (NOMA) has been widely considered as an efficient multiple access scheme for future wireless networks. This is due to the promising performance of NOMA in terms of the larger number of served users and better error performance as compared to traditional multiple access schemes. Therefore, NOMA has received significant research efforts in analyzing its performance under different scenarios and assumptions. In this paper, we analyze the performance of a downlink NOMA scheme considering mobile users, in order to characterize the impact of mobility on the system performance. Specifically, the average bit error rate at mobile users is derived in a closed form expression. The users' mobility is considered to follow the well-known random waypoint mobility model. Mathematical formulas have been verified using Monte Carlo simulations and compared to different scenarios.**

***Index Terms*—Non-Orthogonal Multiple Access; Random Waypoint Mobility; Multiple Access; Mobility.**

I. Introduction

In next-generation wireless networks, the number of connected users is expected to exponentially grow, which implies a significant increase in the demand on spectrum resources. Given the limited spectrum resources, significant research efforts are being performed in designing new spectral-efficient transmission schemes.

The Multiple Access (MA) scheme in a communication system has a paramount importance in improving the overall spectrum efficiency. However, the number of served users in traditional orthogonal MA (OMA) schemes is limited by the number of the available orthogonal spectrum resources. Therefore, non-orthogonal MA (NOMA) schemes have been under investigation for the past years, due to its capability of serving multiple users over the same spectrum resources. There are generally two types of NOMA systems: Power-Domain NOMA (PD-NOMA) and Code-Domain NOMA (CD-NOMA). PD-NOMA schemes focus on serving multiple users with different power levels, where more power is allocated to the user with the weaker channel to ensure user fairness [1], while CD-NOMA schemes focus on optimizing the channel codes and codebook-sequences to separate multiple users [2].

In the literature, many research efforts have been conducted to analyze the performance of NOMA-based systems. In [3], performance analysis for a NOMA-based full duplex cognitive radio network in terms of outage probability was addressed, while in [4], the analysis in terms of outage probability for an uplink cooperative NOMA system with amplify-and-forward protocol has been conducted. In [5], an opportunistic NOMA system with Channel State Information (CSI) available at the transmitter is proposed where its performance is compared with the existing Conventional-NOMA (C-NOMA). Results show that a significant increase in the received data rate is achieved as compared to the C-NOMA system without CSI. In another study [6], a comparison in the bit error rate (BER) is conducted between PD-NOMA and CD-NOMA. In [7], achievable data rate is analyzed for fully-connected and sub-connected hybrid beamforming in NOMA systems operating under both line of sight and non-line of sight scenarios. The outage probability of downlink MIMO systems in vehicular networks is studied in [8] where the maximum ratio-combining technique is used.

While all of the above mentioned works consider fixed-location users only, in [9], a dynamic power allocation NOMA system is proposed for mobile users, where the power is allocated not only based on the user distance from the Base Station (BS), but also on the available transmit power and outage probability. In [10], the impact of mobility on the physical layer security in NOMA systems is studied under the random waypoint (RWP) and random direction (RD) mobility models. In traditional NOMA systems, the users are usually grouped into channel-gain clusters based on each user distance from the BS. However, in mobile users the channel-gain changes continuously which requires re-clustering. In [11], different clustering techniques are discussed for mobile users in NOMA-based systems.

The RWP mobility model has been adopted in many literature works to simulate random mobility of users in different communication networks, as it shows great similarity to practical systems. In [12], RWP mobility model is used for space modulation systems and its effect is analyzed in terms of average BER. In [13] and [14], the effect of mobility in terms of BER and outage probability is studied for Rician and Nakagami-m fading channels respectively. In this paper, we combine both NOMA and RWP to match realistic systems considerations, and we address a comprehensive BER performance analysis of NOMA-based systems considering mobile nodes. Specifically, the average BER at mobile users following the RWP mobility model is derived as an upper bound using the well-known union bounding technique. Closed-form expressions are obtained showing the impact of each one of the scenario parameters.

The rest of the paper is organized as follows. In Section II, the system model presents an overview of NOMA systems and RWP model. In Section III, performance analysis is shown and the BER closed form expression is derived for NOMA systems with mobile users. Finally, the simulations results are explored and conclusion are drawn in Section IV and Section V, respectively.

II. System Model

The considered system model consists of N users that are served by a central BS. The users are assumed mobile users where their mobility pattern follows the well-known Random WayPoint (RWP) mobility model [15]. The instantaneous distance between the n^{th} user ($1 \leq n \leq N$) and the BS is denoted by r_n. According to [16], the the probability density function (pdf) of r_n considering a two-dimensional mobility pattern is expressed as follows

$$f_r(r_n) = \sum_{k=0}^{\mu} \eta_k R^{-\epsilon_k - 1} {r_n}^{\epsilon_k}, \quad \leq r_n \leq R, \tag{1}$$

where $\mu = 3$, $\eta = \frac{12}{73}\{27, -35, 8\}$, and $\epsilon = \{1, 3, 5\}$ for 2D RWP mobility model [16], and R represents the maximum distance. However, to facilitate the implementation of NOMA, it is assumed that r_n in the range $[a_n, b_n]$ (where $b_n > a_n$), which implies that the mobility of a user is considered to be limited within a specific sector around the BS. Accordingly, the pdf of r_n given that $a_n \leq r_n \leq b_n$ is given as follows

$$f_r(r_n) = \frac{\sum_{k=0}^{\mu} \eta_k R^{-\epsilon_k - 1} {r_n}^{\epsilon_k}}{F_r(b_n) - F_r(a_n)}, \tag{2}$$

where $F_r(r_n)$ represents the Cumulative Distribution Function (CDF) of r_n that is expressed as follows

$$F_r(r_n) = \sum_{i=1}^{\mu} \frac{\eta_k}{\epsilon_k + 1} \left(\frac{r_n}{R}\right)^{\epsilon_k + 1}. \tag{3}$$

Notice that R is the maximum distance of the furthest user, i.e., $R = b_N$.

A. PD-NOMA overview

As mentioned earlier, NOMA is a recent multiple access scheme aims at serving multiple users over the same spectrum channel. As such, it has been widely nominated as an efficient solution for spectrum scarcity. In downlink PD-NOMA systems, modulated symbols intended to different users are scaled by different power levels and superimposed together to compose one signal transmitted to all users over a single frequency channel. The strategy of power levels assignment implies that the power level of a user is inversely proportional to the channel conditions of the corresponding user. Therefore, a user of bad channel conditions will get higher power level.

The power level is usually represented by coefficient ρ that is a value between 0 and 1. Thus, ρ_n represents the portion of the total transmit power allocated to the user n, given that $\sum_{n=1}^{N} \rho_n = 1$. Without loss of generality, we consider that $r_1 < r_2 < ... < r_N$ which implies that $\rho_1 < \rho_2 < .. < \rho_n$ as the channel gain is dominated by the separation distance.

In Fig II-A, NOMA system model is illustrated, where the transmitted signal from the BS is obtained by the weighted sum of the power-scaled modulated symbols as follows

$$x = \sum_{n=1}^{N} \sqrt{\rho_n}\, s_n \tag{4}$$

where s_n is the complex modulated symbol for user n drawn from M-ary constellation where M is modulation order.

At the users' sides, the received signal at the n^{th} user, donated by y_n, is expressed as follows

$$y_n = \sqrt{P_t r_n^{-\gamma}}\, h_n x + w_n, \tag{5}$$

where P_t is the transmit power, γ is the path loss exponent and h_n is the channel fading coefficient between the BS and user n that is modeled as Rayleigh fading channel, and w_n is the additive complex white Gaussian noise of σ^2 power.

In this paper, we consider the optimal maximum likelihood (ML) as the detection method used, which implies that each user detects the signals of all users at once. ML detection in NOMA systems is represented as follows

$$\hat{x}_n = \arg \min_{i=1,..,2^{NB}} \left| y_n - \sqrt{p_{r,n}} h_n \odot x^{(i)} \right|^2 \tag{6}$$

where $x^{(i)}$ ($1 \leq i \leq 2^{NB}$) represents the set of the potential transmitted vectors, $p_{r,n} = P_t r_n^{-\gamma}$ is the average received power at user n, and $B = \log_2(M)$.

III. Performance Analysis

In this section the performance analysis in terms of BER will be discussed for the NOMA system. The average BER can be formulated using the union bounding technique [18] as

$$\text{BER}_n = \frac{1}{B\, 2^{NB}} \sum_{i=1}^{2^{NB}} \sum_{i=1}^{2^{NB}} \delta_{ij} \text{PEP}_{i,j}, \tag{7}$$

where δ_{ij} is the number of different bits between the block $x^{(j)}$ and $x^{(i)}$ and $\text{PEP}_{i,j}$ is the pairwise error probability defined as the probability that the symbol $x^{(j)}$ is received given $x^{(i)}$ is transmitted. According to [19], $\text{PEP}_{i,j}$ for NOMA systems considering non-mobile users is given as follows [19]

$$\text{PEP}_{i,j} = \frac{1}{2}\left(1 - \sqrt{\frac{\Gamma_{i,j}}{2 + \Gamma_{i,j}}}\right), \tag{8}$$

where $\Gamma_{i,j} = \frac{p_{r,n} |\Delta_{i,j}|^2}{2\sigma^2}$ and $\Delta_{i,j} = x^{(j)} - x^{(i)}$. However, for mobile users, (8) should be integrated over the pdf of the

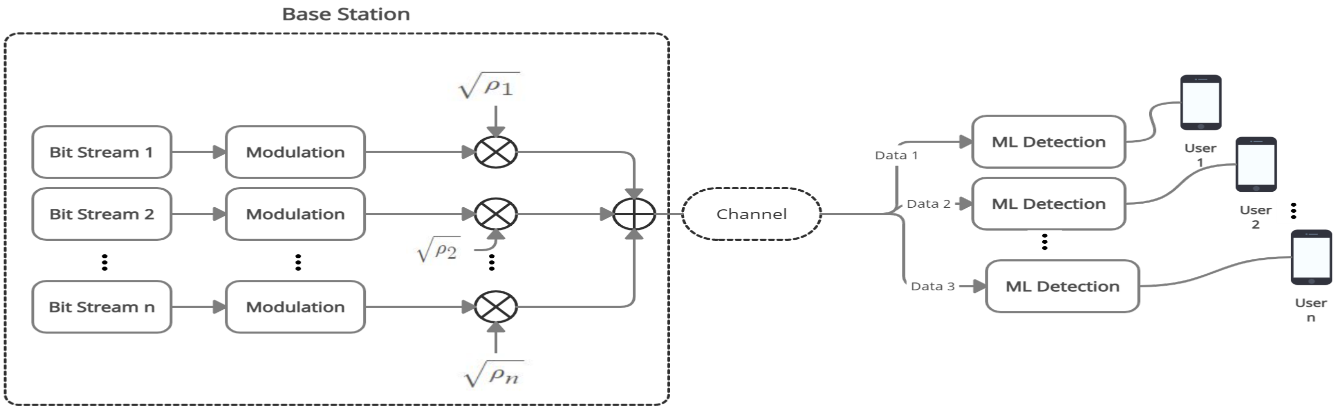

Fig. 1. The block diagram of power domain NOMA with maximum-likelihood detection.

distance r_n from (2), as shown

$$\text{PEP}_{i,j} = \sum_{k=0}^{\mu} \frac{\eta_k R^{-\epsilon_k - 1}}{2\zeta_n} \int_{a_n}^{b_n} r_n^{\epsilon_k} \left(1 - \sqrt{\frac{\Gamma_{i,j}}{2+\Gamma_{i,j}}}\right) \cdot dr_n, \tag{9}$$

where $\zeta_n = F_r(b_n) - F_r(a_n)$. It can be simplified by distributing the integral and performing the integration on the first term to yield

$$\text{PEP}_{i,j} = \sum_{k=0}^{\mu} \frac{\eta_k R^{-\epsilon_k - 1}}{2\zeta_n} \left(\frac{b_n^{\epsilon_k} - a_n^{\epsilon_k}}{\epsilon_k + 1} - \int_{a_n}^{b_n} r_n^{\epsilon_k} \sqrt{\frac{\Gamma_{i,j}}{2+\Gamma_{i,j}}} \cdot dr_n \right) \tag{10}$$

Now, let us define the last integral by I_2 as follows

$$I_2 = \int_{a_n}^{b_n} r_n^{\epsilon_k} \sqrt{\frac{\Gamma_{i,j}}{2+\Gamma_{i,j}}} \cdot dr_n, \tag{11}$$

which can be rewritten as follows

$$I_2 = \int_{a_n}^{b_n} \frac{{r_n}^{\epsilon_k}}{\sqrt{z+1}} \cdot dr_n \tag{12}$$

where $z = \frac{4\sigma^2}{\kappa\, r_n^{-\eta}}$ and $\kappa = P_t \times |\Delta_{i,j}|^2$, The integral can be further expressed by substitution as

$$I_2 = \left(\frac{\kappa}{4\sigma^2}\right)^{\frac{\epsilon_k+1}{\eta}} \frac{1}{\eta} \int_{\frac{4\sigma^2}{K a_n^{-\eta}}}^{\frac{4\sigma^2}{K b_n^{-\eta}}} \frac{z^{\frac{\epsilon_k+1}{\eta}}}{\sqrt{1+z}} \cdot dz \tag{13}$$

which can be expressed in terms of the Fox H-function using [20, eq.1.7.3] as follows

$$I_2 = \frac{\left(\frac{\kappa}{4\sigma^2}\right)^{\frac{\epsilon_k+1}{\eta}}}{\sqrt{\pi}\eta} \int_{\frac{4\sigma^2}{K a_n^{-\eta}}}^{\frac{4\sigma^2}{K b_n^{-\eta}}} z^{\frac{\epsilon_k+1}{\eta}-1} H_{1,1}^{1,1}\left(z \middle| \begin{matrix} (1-0.5,1) \\ (0,1) \end{matrix}\right) \cdot dz \tag{14}$$

where it can be further expressed in Mejier G function using [20, eq. 1.7.1] as follows

$$I_2 = \left(\frac{\kappa}{4\sigma^2}\right)^{\frac{\epsilon_k+1}{\eta}} \frac{1}{\sqrt{\pi}\eta} \int_{\frac{4\sigma^2}{K a_n^{-\eta}}}^{\frac{4\sigma^2}{K b_n^{-\eta}}} z^{\frac{\epsilon_k+1}{\eta}-1} G_{1,1}^{1,1}\left(z \middle| {}^{0.5}_{0}\right) \cdot dz \tag{15}$$

Finally, I_2 can be solved using [21, eq. 2.25.2.2], to yield

$$I_2 = \frac{1}{\sqrt{\pi}\eta} \Bigg[b_n^{\epsilon_k+1} G_{2,2}^{1,2}\left(\frac{4\sigma^2}{\kappa}(b_n)^{\eta} \middle| \begin{matrix} 0.5, 1-\frac{\epsilon_k+1}{\eta} \\ 0, -\frac{\epsilon_k+1}{\eta} \end{matrix} \right) - a_n^{\epsilon_k+1} G_{2,2}^{1,2}\left(\frac{4\sigma^2}{\kappa}(a_n)^{\eta} \middle| \begin{matrix} 0.5, 1-\frac{\epsilon_k+1}{\eta} \\ 0, -\frac{\epsilon_k+1}{\eta} \end{matrix} \right) \Bigg] \tag{16}$$

which can be substituted in (10) to get the final formula of PEP as shown in (17) at the top of the next page. Finally, the resultant PEP can be substituted in (7) to get the average BER of the n^{th} user in NOMA systems considering RWP mobility model, as shown in (18).

IV. Simulation Results

In this section, simulation results of the downlink NOMA systems considering mobile users are explored. Specifically, the average BER at mobile nodes versus the transmit power in dBW are shown considering mobile users according to the 2D-RWP mobility model. As mentioned in the system model section, users are distributed among sectors such that each sector is limited by a minimum distance a_n and a maximum distance b_n. Without loss of generality, in all simulation results, we set $a_{n+1} = b_n$, $b_n - a_n = 200$m and $a_1 = 1$m. The noise power is set to $N_0 = -25$ dB, the path loss exponent is set to $\gamma = 2.7$ and the PSK modulation order is set to $M = 2$. The power coefficients ρ's are computed based on the maximum distance of each user as follows [19]

$$\rho_n = \frac{b_n^2}{\sum_{n=1}^{N} {b_n}^2} \tag{19}$$

Explored results include analytical results that have been obtained using the derived mathematical expression of the average BER at the different users.

Fig. 2 and Fig. 3 depict the average BER versus the transmit power in dBW for a NOMA system considering $N = 2$ users. In both figures, the BER of fixed users at different location are also included for comparison purpose. Specifically, in Fig. 2, the distances of fixed users are assumed to be equal to the maximum distance of each user, i.e., b's, where it can be observed that mobile users can achieve better BER

$$\mathrm{PEP}_{i,j}=\sum_{k=0}^{\mu}\frac{\eta_k R^{-\epsilon_k-1}}{2\zeta_n}\left(\frac{b_n^{\epsilon_k}-a_n^{\epsilon_k}}{\epsilon_k+1}-\frac{1}{\sqrt{\pi}\eta}\left[b_n^{\epsilon_k+1}G_{2,2}^{1,2}\left(\frac{4\sigma^2}{\kappa}\left(b_n\right)^{\eta}\middle|\begin{matrix}0.5,1-\frac{\epsilon_k+1}{\eta}\\0,-\frac{\epsilon_k+1}{\eta}\end{matrix}\right)-a_n^{\epsilon_k+1}G_{2,2}^{1,2}\left(\frac{4\sigma^2}{\kappa}\left(a_n\right)^{\eta}\middle|\begin{matrix}0.5,1-\frac{\epsilon_k+1}{\eta}\\0,-\frac{\epsilon_k+1}{\eta}\end{matrix}\right)\right]\right) \tag{17}$$

$$\mathrm{BER}_n=\frac{1}{B\,2^{NB}}\sum_{i=1}^{2^{NB}}\sum_{i=1}^{2^{NB}}\delta_{ij}\sum_{k=0}^{\mu}\frac{\eta_k R^{-\epsilon_k-1}}{2\zeta_n}\left(\frac{b_n^{\epsilon_k}-a_n^{\epsilon_k}}{\epsilon_k+1}-\frac{1}{\sqrt{\pi}\eta}\left[b_n^{\epsilon_k+1}G_{2,2}^{1,2}\left(\frac{4\sigma^2}{\kappa}\left(b_n\right)^{\eta}\middle|\begin{matrix}0.5,1-\frac{\epsilon_k+1}{\eta}\\0,-\frac{\epsilon_k+1}{\eta}\end{matrix}\right)-a_n^{\epsilon_k+1}G_{2,2}^{1,2}\left(\frac{4\sigma^2}{\kappa}\left(a_n\right)^{\eta}\middle|\begin{matrix}0.5,1-\frac{\epsilon_k+1}{\eta}\\0,-\frac{\epsilon_k+1}{\eta}\end{matrix}\right)\right]\right) \tag{18}$$

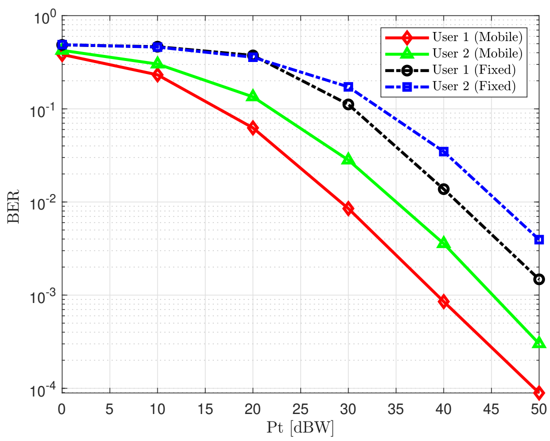

Fig. 2. BER performance comparison between mobile users and fixed users in downlink PD-NOMA system (2 users) (Fixed users are at maximum distance)

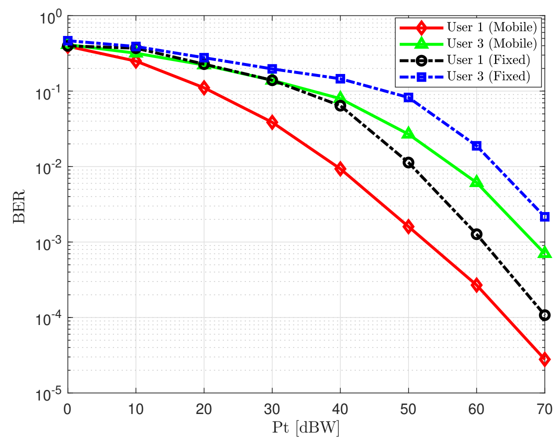

Fig. 4. BER performance comparison between mobile users and fixed users in downlink PD-NOMA system (3 users) (Fixed users are at maximum distance)

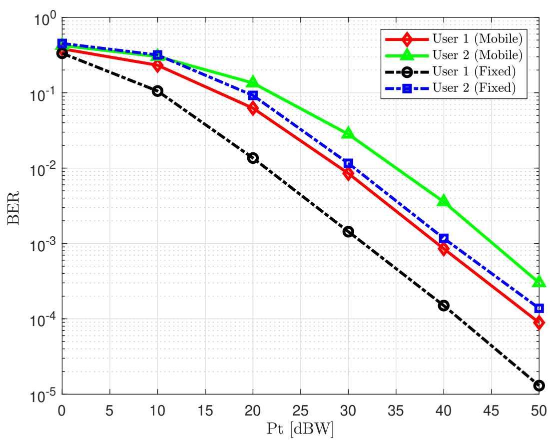

Fig. 3. BER performance comparison between mobile users and fixed users in downlink PD-NOMA system (2 users) (Fixed users are at minimum distance)

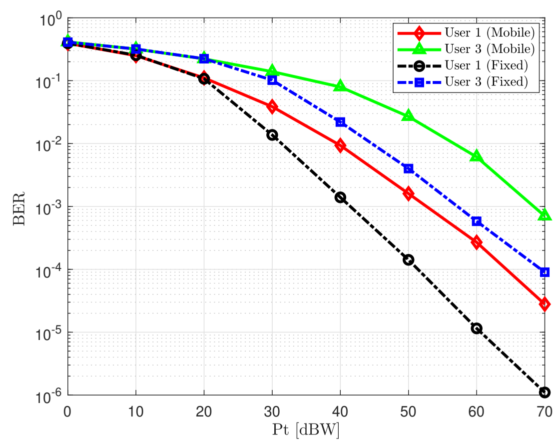

Fig. 5. BER performance comparison between mobile users and fixed users in downlink PD-NOMA system (3 users) (Fixed users are at minimum distance)

due to the less distances considered. On the other hand, in Fig. 3, the distances of fixed users are assumed to be equal to the minimum distance of each user, i.e., a's, where it can be observed that mobile users worse BER due to the larger distances considered. The same simulations are conducted considering a system of $N = 3$ users and results are plotted in Fig. 4 and Fig. 5 where the same observations can be taken.

In Fig. 6 and Fig. 7, the analytical results of the average BER versus the transmit power for $N = 2$ users and $N = 3$ users are shown, respectively. It can be clearly observed that the analytical results obtained by the derived mathematical formula in (18) act as upper bounds of the simulation results. The gap in the low transmit power range is due to the very low SNR values. However, as the transmit power increases, the gap diminishes and analytical and simulation results match each other.

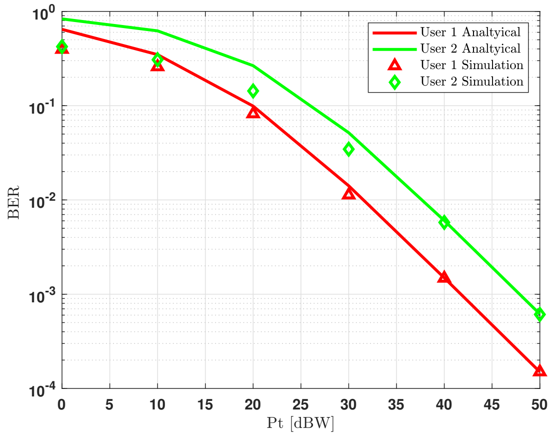

Fig. 6. The average BER versus the transmit power for downlink PD-NOMA system of two users.

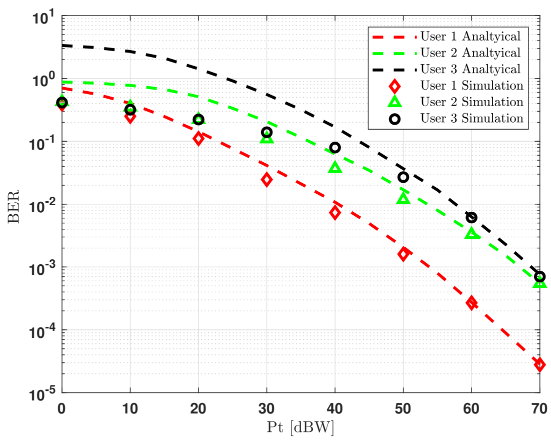

Fig. 7. The average BER versus the transmit power for downlink PD-NOMA system of three users.

V. Conclusions

The error performance of downlink power domain non-orthogonal multiple access systems considering mobile users, based on random waypoint model, is evaluated in this paper. The average bit error rate has been derived in a closed form expression and validated through simulation results. A comparison between the performance at mobile users and the performance of fixed users has been also conducted in this paper, for a better results illustration.

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References

[1] M. Alzard, S. Althunibat, K. Umebayashi and N. Zorba, "Performance Analysis of Resource Allocation in THz-Based Subcarrier Index Modulation Systems for Mobile Users," *IEEE Access*, vol. 9, pp. 129771-129781, 2021.

[2] Z. Liu and L. L. Yang, "Sparse or Dense: A Comparative Study of Code-Domain NOMA Systems," IEEE Transactions on Wireless Communications, 2021.

[3] V. S. Babu, N. Deepan and B. Rebekka, "Performance Analysis of Cooperative Full Duplex NOMA system in Cognitive Radio Networks," *2020 International Conference on Wireless Communications Signal Processing and Networking (WiSPNET), 2020*, pp. 84-87.

[4] X. Xie, Y. Bi and X. Nie, "Performance Analysis of Uplink Cooperative NOMA System with an AF Relay," *2020 IEEE 20th International Conference on Communication Technology (ICCT),* 2020, pp. 178-181.

[5] P. K. Jha, S. S. Shree and D. S. Kumar, "An opportunistic-non orthogonal multiple access based cooperative relaying system over Rician fading channels," *2018 4th International Conference on Recent Advances in Information Technology (RAIT),* 2018, pp. 1-5.

[6] Q. Luo et al., "An Error Rate Comparison of Power Domain Non-Orthogonal Multiple Access and Sparse Code Multiple Access," *IEEE Open Journal of the Communications Society,* vol. 2, pp. 500-511, 2021.

[7] A. A. Badrudeen, C. Y. Leow and S. Won, "Performance Analysis of Hybrid Beamforming Precoders for Multiuser Millimeter Wave NOMA Systems," *IEEE Transactions on Vehicular Technology,* vol. 69, no. 8, pp. 8739-8752, Aug. 2020.

[8] L. Li and T. Wu, "Performance Analysis of Downlink MIMO NOMA Vehicular Networks," *2020 IEEE International Conference on Information Technology,Big Data and Artificial Intelligence (ICIBA)*, 2020, pp. 1483-1486.

[9] B. Narottama and S. Y. Shin, "Dynamic Power Allocation for Non-Orthogonal Multiple Access with User Mobility," *2019 IEEE 10th Annual Information Technology, Electronics and Mobile Communication Conference (IEMCON),* 2019, pp. 0442-0446.

[10] J. Tang, L. Jiao, N. Wang, P. Wang, K. Zeng and H. Wen, "Mobility Improves NOMA Physical Layer Security," *2018 IEEE Global Communications Conference (GLOBECOM),* 2018, pp. 1-6.

[11] M. K. Naeem, R. Abozariba, M. Asaduzzaman and M. Patwary, "Towards the Mobility Issues of 5G-NOMA Through User Dissociation and Re-association Control," *2020 IEEE 21st International Symposium on "A World of Wireless, Mobile and Multimedia Networks" (WoWMoM),* 2020, pp. 427-432.

[12] S. Althunibat, O. S. Badarneh and R. Mesleh, "Random Waypoint Mobility Model in Space Modulation Systems," *IEEE Communications Letters,* vol. 23, no. 5, pp. 884-887, May 2019.

[13] M. Alzard, S. Althunibat, K. Umebayashi and N. Zorba, "Resource Allocation in THz-based Subcarrier Index Modulation Systems for Mobile Users," IEEE Global Communications Conference (GLOBECOM), 2021.

[14] V. A. Aalo, C. Mukasa and G. P. Efthymoglou, "Effect of Mobility on the Outage and BER Performances of Digital Transmissions over Nakagami-Fading Channels," *IEEE Transactions on Vehicular Technology,* vol. 65, no. 4, pp. 2715-2721, April 2016.

[15] E. Hyytia et al., "Spatial node distribution of the random waypoint mobility model with applications", *IEEE Trans. Mobile Computing,* vol. 5, no. 6, pp. 680-694, 2006.

[16] V. Aalo et al., "Effect of mobility on the outage and BER performances of digital transmissions over Nakagami-m fading channels." *IEEE Trans. Veh. Technol.*, vol. 65, no. 4, pp. 2715-2721, Apr. 2016.

[17] K. Govindan et al., "Probability density of the received power in mobile networks", *IEEE Trans. Wireless Commun.,* 10(11), pp. 3613-3619, 2001.

[18] J. G. Proakis, *Digital Communications*. McGraw–Hill, 1995.

[19] A. Almohamad, S. Althunibat, M. Hasna and K. Qaraqe, "On the Error Performance of Non-orthogonal Multiple Access Systems," *2020 International Conference on Information and Communication Technology Convergence (ICTC),* pp. 116-121, 2020.

[20] A. M. Mathai and S. R. Kumar, *The H-function with applications in statistics and other disciplines*. New Delhi: Wiley Eastern, 1978.

[21] A. P. Prudnikov et al., *Integrals and series: in Russian*, vol. 3, 1986.