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RESEARCH ARTICLE

Physical Layer Security in N-Pair NOMA-PLNC Wireless Networks

SAMIKKANNU RAJKUMAR[1], (Member, IEEE),
DUSHANTHA NALIN K. JAYAKODY[1,2,4], (Senior Member, IEEE),
REEM ALKANHEL[3], (Member, IEEE),
AND AMMAR MUTHANNA[1,5], (Senior Member, IEEE)
[1]Centre for Telecommunication Research, School of Engineering, Sri Lanka Technological Campus, Padukka 10500, Sri Lanka
[2]Autónoma TechLab, Centro de Investigação em Tecnologias, Universidade Autónoma de Lisbon, 1169-023 Lisboa, Portugal
[3]Department of Information Technology, College of Computer and Information Sciences, Princess Nourah bint Abdulrahman University, Riyadh 11671, Saudi Arabia
[4]School of Computer Science and Robotics, Tomsk Polytechnic University, 634050 Tomsk, Russia
[5]Department of Applied Probability and Informatics, Peoples' Friendship University of Russia (RUDN University), 117198 Moscow, Russia

Corresponding authors: Dushantha Nalin K. Jayakody (nalin.jayakody@ieee.org) and Reem Alkanhel (rialkanhal@pnu.edu.sa)

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ABSTRACT In this paper, the effective end-to-end secure communication of N-pair cellular network is studied. Promising multiple access scheme known as non-orthogonal multiple access (NOMA) and physical layer network coding (PLNC) scheme are employed to improve the spectral and the temporal efficiency respectively. Also, this proposed model uses the physical layer security to ensure the secure wireless communication. It is assumed that the eavesdropper (Eve) tries to trace the confidential message from the legitimate user's. Hence, they generates the artificial noise (AN) to confuse the Eve. Closed form expression for the end-to-end outage probability of the proposed N-pair NOMA-PLNC wireless network is derived. Further, a closed form expression for the secrecy outage probability of the proposed network is derived using homogeneous Poisson point process (HPPP) and Gaussian-Laguerre quadrature. Numerical results are presented to validate theoretical findings. It is noteworthy that uplink performance of the proposed network is better than the network without PLNC scheme.

INDEX TERMS Non-orthogonal multiple access, physical layer network coding, physical layer security.

I. INTRODUCTION

Recent release of third generation partnership project (3GPP-v17) extensively studied non-orthogonal multiple access (NOMA) scheme with practical experiments particularly for the signal transmission and multi-user receivers model such as minimum mean square error (MMSE) hard-interference cancellation and elementary signal estimator with soft input soft output decoder [1]. Applications of the NOMA scheme extended to various fields in sixth generation (6G) communication and it is expected that 6G wireless networks will offer 1000 times higher wireless connectivity than the fifth generation (5G) networks. 6G also provides the ultra long distance communication with low latency. In particular, demand on the large wireless accessibility occurs in the low power massive machine type communication (mMTC) and in fact it is one of the major requirements of the 6G communications. In mMTC wireless networks, network congestion problem is the major issue. In such scenarios, a promising non-orthogonal multiple access (NOMA) scheme is applied in the MTC networks to support the massive access and thereby reduce the network congestion [2].

Basically, NOMA scheme allows many users to share the same time/frequency resource block (RB) to achieve the better spectral efficiency and the massive connectivity in the cellular network [3]. Currently, cellular network

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is operating with orthogonal frequency division multiple access (OFDMA) scheme and it can be replaced by NOMA scheme in the future implementation of the cellular systems. Among the various NOMA schemes, power domain NOMA is the preferable one due to its adaptable design architecture. Power domain NOMA scheme employs the superposition coding (SC) at the transmitter and the successive interference cancellation (SIC) at the receiver [4]. Since the user rate enhancement is the key benefit of the NOMA scheme, target of the many researchers are primarily on the outage analysis of the channel links [5], [6], [7], [8]. For instance, the outage performance of the NOMA based downlink cellular wireless network is analyzed under randomly deployed users in [5]. In this model, the outage of the N users NOMA system is analyzed with respect to the user target data rate. Similarly, the outage of the downlink NOMA system is analyzed with known channel state information (CSI) at the transmitter and its performance is improved by optimizing the power allocation [6]. Further, the outage performance of the NOMA system is analyzed over Nakagami-m fading channels [7] using cumulative distribution function (CDF) based scheduling. Recently, the outage of the uplink NOMA based land-mobile satellite (LMS) system is analyzed over composite shadowed-Rician fading channels [8].

In day-to-day life, people are using the mobile applications frequently for sharing some confidential messages such as bank details, e-health data, command messages in military services and control messages in industrial operations. Therefore, secure communication is another important aspects [9]. Although, the wireless networks employ the bit-level cryptography for secure transmission, there is no guarantee to protect confidential messages in the public wireless networks. To tackle these issues, a new idea is proposed to provide security in physical layer from the information theoretical point of view [10]. In physical layer, secure transmission is achieved through various ways such as artificial noise (AN), beam-forming, diversity and secret key [11]. Recently, several works are proposed in the NOMA wireless networks using the physical layer security. Particularly, AN used in [12] for secure communication of the large-scale NOMA wireless network and AN is generated by the authorized user in order to confuse the eavesdropper (Eve) while receiving the confidential messages. Similarly, wireless powered full-duplex relay is applied in the cooperative NOMA wireless network to improve the secure communication and the ergodic secrecy sum rate in [13].

In practical wireless networks, the presence of interference is unavoidable one due to its broadcast nature. However, by properly aligning the interference signal with the transmitted signal it will help to improve the performance of the wireless network. With that inspiration, initially the concept of physical layer network coding (PLNC) scheme is developed in [14] to boost the data rate of the wireless network. PLNC scheme is working on two phases such as the multiple access phase and the broadcast phase and it is termed as orthogonal multiple access channel (OMAC) and non-orthogonal broadcast channel (NOBC) as in Figure 2. In first phase, users pair who wants to exchange their messages will send their data to the base station simultaneously, then the base station decodes the linear combination of received signal and then perform the XOR operation to generate the PLNC signal. In second phase, base station transmits the resulting decoded and re-modulated signal to the same user pair through the broadcast channel, finally the user will decode the received signal using its own message. In the past few years, many of the works have been proposed in the PLNC based relay networks, for example, in a large scale cellular network, PLNC scheme is applied to increase the capacity of the network [15]. Similarly, in [16] the bit error rate (BER) performance of the bidirectional relay network is analyzed using binary phase shift keying (BPSK) modulation.

Recently, various wireless networks model using NOMA and PLNC schemes are proposed to enhance the user rate in the cellular wireless network [17], [18], [19]. The main impact of the PLNC scheme comes from the fact of temporal efficiency which indirectly increase the user accessibility. Therefore, combining NOMA with PLNC scheme is the promising model for the future wireless networks. More recently a simple two-pair NOMA-PLNC wireless network is proposed to improve the sum-rate through optimal power allocation in [18] and [19]. Multi-user detection is performed in the NOMA-PLNC network using the cascade computation decoding algorithm in [20]. Two-way relay based NOMA network is analyzed with perfect and imperfect-SIC through independent non-identically distributed (*ind*) fading channels in [21]. Indeed, the spectral efficiency of the PLNC network is improved through cooperative NOMA scheme in [22]. Interestingly, the far user signal strength is improved in the NOMA-PLNC wireless network using the existing backscatter devices in [23].

A. MOTIVATION AND CONTRIBUTION

Although some of the works are proposed using NOMA-PLNC scheme [17], [18], [19], [20], [21], [22], [23], study of such a network with N-pair of users is still an open issue. Practically, each cell in the cellular network is operating with large number of users, hence it is necessary to develop a suitable cellular network model with N user's pair. Further, providing secure transmission in the cellular networks is another major concern. Recently, few works are proposed in the cellular networks to establish the security in the physical layer [24], [25], [26]. For instance, secrecy outage of the 5G cellular network is analyzed and secrecy throughput is enhanced using access threshold metric in [24]. Further, secrecy rate of the cellular network is analyzed under full-duplex and it is the promising technology in upcoming wireless networks [25]. Similarly, secrecy rates of the downlink cellular networks are analyzed and locations of the base station and mobile users are modeled using Poisson distribution in [26]. Further, relay selection assisted secrecy outage of the downlink NOMA wireless network is studied in [27].

In other hand, secrecy outage of the uplink NOMA based cellular network is analyzed in [28] by considering inter-cell and intra-cell interference's. Further, secure transmission in NOMA wireless networks is achieved through chaos modulation in [29] and [30]. By considering all the issues in the NOMA based cellular networks it is noted that the user pairing using PLNC scheme is not yet considered even though it provides significant improvement in the overall network performance. Therefore, in this paper a new NOMA-PLNC based N-pair cellular network model is proposed in the presence of Eve. In this proposed model, each pair of users occupy a unique time slot to transmit the signal to the base station through OMAC link and then base station linearly combine all the PLNC signals using superposition coding. Then, the resulting NOMA signal is transmitted back to all the users simultaneously through NOBC link. The main contributions of this paper are:

- N-pair NOMA-PLNC based wireless cellular network in the presence of Eve. At initial stage, a two-pair network model is considered then it is extended to N-pair wireless network. Further, the network is studied with and without Eve.
- Locations of the users are modeled using Poisson process to analyze the secrecy outage of the proposed NOMA-PLNC wireless network. Further, the proposed model is analyzed without considering Eve through Rayleigh's fading.
- Closed form expression for the end-to-end outage probability of the two-pair NOMA-PLNC wireless network is derived and it is extended to N pairs NOMA-PLNC wireless cellular network.
- Also, closed form expression for the secrecy outage probability of the downlink NOMA-PLNC network is derived.

The rest of the paper is organized as follows: In section II, the system model of the proposed wireless network is discussed. Derivations for the outage of the OMAC phase, NOBC phase, N-pair NOMA and secrecy outage are discussed in section III. Numerical results of the proposed network are presented in section IV and concluding remarks are given in section V.

II. SYSTEM MODEL

The proposed cellular network consist of one base station, N near users and M far users and they are distributed randomly in the presence of the Eve as shown in Figure 1.[1] The density of the distribution of the legitimate users are modeled according to the homogeneous Poisson point process (HPPP) [12]. It is assumed that the N near users are distributed within the inner circular region with radius of r_n and M far users are distributed in the annular region (i.e, intersection of inner and outer circular region) with its outer radius of r_f. In this model, the user pair is formed by combining one near user and one far user and each pair communicate with each other using NOMA and PLNC schemes. Since, data is exchanged between the user's through base station, it is treated as a two way communication. Further, it is assumed that the Eve is located beside the legitimate user to trace the confidential information. Therefore to safeguard from the Eve, the legitimate user is operating with full-duplex (FD) mode and emits the AN while receiving the message from the base station in order to confuse the Eve.

[1]Here it is assumed that the near user is strong user and the far user is weak user although practically it may be change.

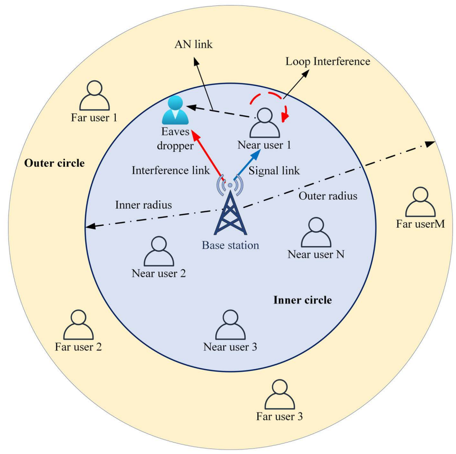

FIGURE 1. Geometric model of the N-pair NOMA-PLNC wireless network.

In this model, the data transmission is performed in two phases such as OMAC phase and NOBC phase [18] as shown in Figure 2. Assume that base station is acting as a half-duplex decode-and-forward (DF) relay. In OMAC phase, each pair send their data to the base station in the respective time slot. At $M = N$, N number of user pairs are formed. Thus, N-pair of users transmits their data using N time slots. However, MN time slots are needed for this uplink transmission without the PLNC scheme. Then, base station perform the decoding operation to the received signal and apply the XOR operation to generate the PLNC signals. In NOBC phase, all the resulting PLNC signals are combined into a single NOMA signal. Then the resulting NOMA signal is transmitted by the base station to all the users simultaneously. Thus, the spectral and temporal efficiency of the proposed 5G wireless network is significantly improved. In this scenario, it is assumed that Eve's traces the information from the each pair of user's which is discussed in detail in subsection C.

A. AN OMAC PHASE

The i^{th} pair received signal $y_{\text{OMAC},i}$ at the base station over an OMAC link is given by

$$y_{\text{OMAC},i} = \sqrt{P_i} s_{i,1} g_{i,1} + \sqrt{P_i} s_{i,2} g_{i,2} + n_i. \tag{1}$$

where P_i denotes the i^{th} user pair transmit power, $s_{i,1}$ and $s_{i,2}$, $1 \leq \mathrm{i} \leq N$ are the BPSK modulated data signals sent by the $\mathrm{U}_{i,1}$ and $\mathrm{U}_{i,2}$ and its average values are $\mathbb{E}(|s_{i,1}|^2) = \mathbb{E}(|s_{i,2}|^2) = 1$ [21], $g_{i,1}$, $g_{i,2}$ are the channel coefficients from

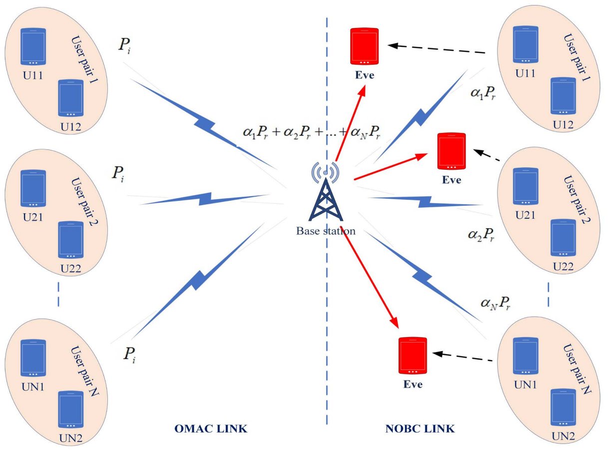

FIGURE 2. **Signal transmission in N-pair NOMA-PLNC wireless network.**

$U_{i,1}$ and $U_{i,2}$ to base station and its squared magnitudes follows the exponential distribution with mean $\mu_{i,1}$ and $\mu_{i,2}$ [39] respectively and its inverse denoted as $1/\mu_{i,j} = \upsilon_{i,j}$, $j \in (1, 2)$, n_i is the complex independent identically distributed (*iid*) additive white Gaussian noise (AWGN) with mean μ and the variance σ^2, i.e., $n_i \sim \mathcal{CN}(\mu, \sigma^2)$.

B. A NOBC PHASE WITHOUT EVE

In the absence of the Eve, the near users are simply applying the SIC operation to decode its own message and does not generate the AN signal, thus the full-duplex is absent in this scenario.

The XORed version of the i^{th} pair signals at the base station can be written as $s_{i,r} = s_{i,1} \oplus s_{i,2}$ [14], [16]. Then, all the XORed signals are linearly combined with different power levels α_i, $1 \leq i \leq N$ using NOMA scheme and it can be written as $s_r = \sum_{i=1}^{N} \alpha_i \sqrt{P_r} s_{i,r}$, where P_r is the base station transmit power. Further, the power allocation coefficient α_i will satisfy the condition $\alpha_1 > \alpha_2, \ldots, \alpha_{N-1} > \alpha_N$ and $\alpha_1 + \alpha_2 + \ldots + \alpha_N = 1$ [21].

The base station transmits a NOMA signal s_r to all the N users pair simultaneously. The signal received at the i, j^{th} user, $U_{i,j}$ of i^{th} pair can be written as

$$y_{\text{NOBC},i,j} = s_r g_{i,j} + n_{i,j}. \tag{2}$$

where $g_{i,j}$ is the channel coefficient from base station to the i, j^{th} user, $U_{i,j}$ and it's squared magnitude modeled as an independent non-identically distributed (*ind*) random variable follows the exponential distribution with parameter $\upsilon_{i,j} = 1/\mu_{i,j}$, $n_{i,j}$ is the Gaussian noise.

C. A NOBC PHASE WITH EVE

In this case, both near and far users are adopting full-duplex mode of operation, hence the received signals of users are affected by the loop interference (LI) signal [12]. Although each user's affected with LI, AN from neighboring users and inter-pair interference's, it is reasonable to consider only LI power since the power of LI is more dominant one to the user performance [35], [36]. However, analyzing the impact of AN signals from many users and inter-pair interference can be considered as a future scope of this work. Therefore, the received signal of the i^{th} pair near user in the presence of LI can be written as

$$y_{\text{NOBC}}^{\text{near}} = s_r g_{\text{bn}} + g_{\text{LI}} \sqrt{P_i} s_{\text{AN}} + n_i. \tag{3}$$

where $g_{\text{bn}} = \frac{g_{i,j}}{1+d_{\text{bn}}^{\alpha}}$ [35] is the combined small and large scale fading channel coefficient from the base station to the near user which ensure the user distribution in the circular region, d_{bn} is the distance from the base station to the near user, α is the path loss exponent. g_{LI} is the channel coefficient of the LI which follow the exponential distribution with parameter $\upsilon_{\text{LI}} = 1/\mu_{LI}$, s_{AN} is the AN signal which is designed using pseudo noise (PN). With the assumption of the perfect SIC [12], the signal-to-interference plus noise ratio (SINR) of the i^{th} pair near user in the presence of LI can be written as

$$\gamma_{\text{near}} = \frac{|g_{\text{bn}}|^2 \alpha_i P_r}{|g_{\text{LI}}|^2 P_{\text{LI}} + \sigma^2}. \tag{4}$$

where $P_{\text{LI}} = \sqrt{P_i} \mathbb{E}(|s_{\text{AN}}|^2)$ is the LI power, α_i is the power allocation coefficient of the near user. Similarly, SINR of the i^{th} pair far user can be given as

$$\gamma_{\text{far}} = \frac{|g_{\text{bf}}|^2 \alpha_{i+1} P_r}{|g_{\text{bf}}|^2 \alpha_i P_r + |g_{\text{LI}}|^2 P_{\text{LI}} + \sigma^2}. \tag{5}$$

where $g_{\text{bf}} = \frac{g_{i,j}}{1+d_{\text{bf}}^{\alpha}}$ is the channel between the base station and the far user, d_{bf} is the distance from the base station to the far user and α_{i+1} is the power allocation coefficient of the far user. At the same time, Eve traces the near user message from the base station meanwhile the near use send the AN signal to the Eve. Thus, the received signal at Eve can be written as

$$y_{\text{NOBC}}^{\text{Eve}} = s_r g_{\text{be}} + g_{\text{ne}} \sqrt{P_i} s_{\text{AN}} + n_i. \tag{6}$$

where $g_{\text{be}} = \frac{g_{i,j}}{1+d_{\text{be}}^{\alpha}}$, d_{be} is the distance from the base station to the Eve, $g_{\text{ne}} = \frac{g'_{\text{ne}}}{1+d_{\text{ne}}^{\alpha}}$ is the channel coefficient from the near user to the Eve. It is assumed that Eve has capability to detect multi user's signal [12], [35]. Therefore, SINR of the Eve with respect to the near user can be written as

$$\gamma_{\text{Eve,n}} = \frac{|g_{\text{be}}|^2 \alpha_i P_r}{|g_{\text{ne}}|^2 P_{\text{AN}} + \sigma^2}. \tag{7}$$

where P_{AN} is AN power which is identical to the LI power. Similarly, SINR of the Eve with respect to the far user is given by

$$\gamma_{\text{Eve,f}} = \frac{|g_{\text{be}}|^2 \alpha_{i+1} P_r}{|g_{\text{be}}|^2 \alpha_i P_r + |g_{\text{fe}}|^2 P_{\text{AN}} + \sigma^2}. \tag{8}$$

where $g_{\text{fe}} = \frac{g'_{\text{fe}}}{1+d_{\text{fe}}^{\alpha}}$ is the channel coefficient from the far user to the Eve.

III. OUTAGE PROBABILITY ANALYSIS

In this section, the end-to-end outage performance of the proposed N-pair NOMA-PLNC network is studied. For simplicity, we first derive the outage performance of the two-pair NOMA-PLNC wireless network and then it is extended to the N-pair NOMA-PLNC network.

A. OUTAGE PROBABILITY IN AN OMAC LINK

Let us consider i^{th} and $(i+1)^{\text{th}}$ pair signal to noise ratio (SNR) as $\gamma_{i,1}$, $\gamma_{i,2}$, $\gamma_{(i+1),1}$, $\gamma_{(i+1),2}$ and they can be written as

$$\gamma_{i,1} = \frac{|g_{i,1}|^2 P_i}{\sigma^2}; \quad \gamma_{i,2} = \frac{|g_{i,2}|^2 P_i}{\sigma^2}. \tag{9}$$

$$\gamma_{(i+1),1} = \frac{|g_{(i+1),1}|^2 P_i}{\sigma^2}; \quad \gamma_{(i+1),2} = \frac{|g_{(i+1),2}|^2 P_i}{\sigma^2}. \tag{10}$$

Using (9) and (10), the outage probability of an OMAC link can be expressed as

$$p_{\text{out}}^{\text{OMAC}}(R) = Pr(\min[\min(\gamma_{i,1}, \gamma_{i,2}), \min(\gamma_{(i+1),1}, \gamma_{(i+1),2})] < \gamma_1). \tag{11}$$

where $\gamma_1 = 2^{2R/W} - 1$ is the threshold SNR, W is the channel bandwidth which is assumed to be 1. Let $\gamma_a = \min(\gamma_{i,1}, \gamma_{i,2})$ and $\gamma_b = \min(\gamma_{(i+1),1}, \gamma_{(i+1),2})$, then (11) can be rewritten as

$$p_{\text{out}}^{\text{OMAC}}(R) = Pr(\underbrace{\min(\gamma_a, \gamma_b)}_{\text{OMAC link}} < \gamma_1). \tag{12}$$

Using the probability theory, $Pr(\min(a, b))$ can be further simplified as [37]

$$p_{\text{out}}^{\text{OMAC}}(R) = \underbrace{Pr(\gamma_a < \gamma_1)}_{\text{C}_1} + (1 - Pr(\gamma_a < \gamma_1))\underbrace{Pr(\gamma_b < \gamma_1)}_{\text{C}_2}. \tag{13}$$

In (13), first term C_1 can be computed by substituting $\gamma_a = \min(\gamma_{i,1}, \gamma_{i,2})$ as follows,

$$\text{C}_1 = Pr(x < \frac{\gamma_1}{\rho}) + (1 - Pr(x < \frac{\gamma_1}{\rho}))Pr(y < \frac{\gamma_1}{\rho}). \tag{14}$$

where $\rho_i = \frac{P_i}{\sigma^2}$ is the SNR of each user and it is assumed constant for all users, $\rho_i \approx \rho$, $x = |g_{i,1}|^2$ and $y = |g_{i,2}|^2$. After some mathematical manipulation's, C_1 can be computed as

$$\text{C}_1 = 1 - e^{-\frac{\gamma_1}{\rho}(\frac{\upsilon_{i,1}+\upsilon_{i,2}}{\upsilon_{i,1}\upsilon_{i,2}})}. \tag{15}$$

Similarly, the second term C_2 can be obtained as

$$\text{C}_2 = 1 - e^{-\frac{\gamma_1}{\rho}(\frac{\upsilon_{(i+1),1}+\upsilon_{(i+1),2}}{\upsilon_{(i+1),1}\upsilon_{(i+1),2}})}. \tag{16}$$

By substituting C_1 and C_2 in (13), the outage probability of an OMAC link can be determined as

$$p_{\text{out}}^{\text{OMAC}}(R) = 1 - e^{-\frac{\gamma_1}{\rho}(\upsilon_{a_i}+\upsilon_{b_i})}. \tag{17}$$

where $\upsilon_{a_i} = (\frac{\upsilon_{i,1}+\upsilon_{i,2}}{\upsilon_{i,1}\upsilon_{i,2}})$ and $\upsilon_{b_i} = (\frac{\upsilon_{(i+1),1}+\upsilon_{(i+1),2}}{\upsilon_{(i+1),1}\upsilon_{(i+1),2}})$.

B. OUTAGE PROBABILITY IN NOBC LINK

In NOBC link, user can decode its message in two stages. In first stage, user perform the SIC operation to decode its own PLNC signal. Thus in the downlink, the near user first decode the far user PLNC signal and it will be removed from the received signal then the near user decode its own PLNC signal. After that user will do the XOR operation with the decoded PLNC signal and its own message to get the final decoded message.

The SINR of the i, j^{th} far user to decode its own message can be written as

$$\gamma_{\text{far}\rightarrow\text{near}} = \underbrace{\frac{|g_{i,j}|^2 \alpha_1 P_r}{|g_{i,j}|^2 \alpha_2 P_r + \sigma^2}}_{\text{NOBC link}}. \tag{18}$$

where $\alpha_1 > \alpha_2$, after removing the far user signal, the SNR of the near user is given by

$$\gamma_{\text{near}} = \frac{|g_{i,j}|^2 \alpha_2 P_r}{\sigma^2}. \tag{19}$$

Using (12) and (18), the end-to-end outage probability of the far user pair can be expressed as [21]

$$p_{\text{out}}^{\text{E-to-E}}(R) = Pr(\min(\text{OMAC link, NOBC link}) < \gamma_2). \tag{20}$$

where $\gamma_2 = 2^{3R} - 1$, it can be further modified as

$$p_{\text{out}}^{\text{E-to-E}}(R) = Pr(\text{OMAC link} < \gamma_2) + (1 - Pr(\text{OMAC link} < \gamma_2))Pr(\text{NOBC link} < \gamma_2). \tag{21}$$

After simplifying, the end-to-end outage probability of the proposed NOMA-PLNC network can be determined as

$$p_{\text{out}}^{\text{E-to-E}}(R) = 1 - e^{-\frac{\gamma_2}{\rho}(\upsilon_a+\upsilon_b+\upsilon_c)}. \tag{22}$$

where $\upsilon_c = \frac{1}{(\alpha_1-\alpha_2\gamma_2)\upsilon_{i,j}}$ and $\alpha_1 > \alpha_2\gamma_2$.

Proof: See Appendix A.

C. OUTAGE PROBABILITY OF N-PAIR USERS

Let $\Gamma_i = \min(\gamma_{i,1}, \gamma_{i,2})$ and $i \in (1, N)$ is the received SNR of the i^{th} pair at the base station. In this model, the possible outage at the base station is calculated by: 1) if either of the users in the pair is not successful at the base station or 2) if any pair at the base station is not successful. Therefore, the outage probability of the each user in N-pair OMAC link can be expressed as

$$p_{\text{out},N}^{\text{OMAC}}(R) = Pr(\min(\Gamma_1, \Gamma_2, \ldots, \Gamma_N) < \gamma_3). \tag{23}$$

where $\gamma_3 = 2^{NR} - 1$ is the threshold SNR. Let $\Gamma_a = \Gamma_2, \Gamma_3, \ldots, \Gamma_N$, then it can be rewritten as

$$p_{\text{out},N}^{\text{OMAC}}(R) = Pr(\min(\Gamma_1, \Gamma_a) < \gamma_3). \tag{24}$$

Then, the ouatge probability of the N-pair OMAC link can be written as

$$p_{\text{out},N}^{\text{OMAC}}(R) = Pr(\Gamma_1 < \gamma_3) + (1 - Pr(\Gamma_1 < \gamma_3))Pr(\Gamma_a < \gamma_3). \tag{25}$$

By expanding (25), N-pair OMAC link outage probability becomes

$$p_{\text{out},N}^{\text{OMAC}}(R) = Pr(\Gamma_1 < \gamma_3) + (1 - Pr(\Gamma_1 < \gamma_3)) (\Gamma_2 < \gamma_3) + (1 - Pr(\Gamma_2 < \gamma_3))\ldots (\Gamma_{N-1} < \gamma_3) + (1 - Pr(\Gamma_{N-1} < \gamma_3)) Pr(\Gamma_N < \gamma_3). \quad (26)$$

After simplification, the final expression for the outage probability of the N-pair OMAC link can be computed as

$$p_{\text{out},N}^{\text{OMAC}}(\text{R}) = 1 - e^{-\frac{\gamma_3}{\rho}(\sum_{i=1}^{N} \upsilon_{a_i} + \upsilon_{b_i})}. \quad (27)$$

In base station, each pair of the received signal are decoded and then XORed to obtain PLNC signal. After that, all the PLNC signals are combined linearly with unique power levels α_i, $i\in(1, N)$ using NOMA then the resulting signal is transmitted to all the users simultaneously.

Note that in the downlink, each pair of signal is a PLNC signal, hence the receiver first decode the PLNC signal and then it can decode the original message by multiplying decoded PLNC signal with its own signal [23]. As per the NOMA scheme, the i^{th} pair apply the SIC operation to decode its message as follows, first it decode the $(i+1)^{\text{th}}$ to N^{th} pair messages using SIC operation then it will be removed from the received signal, after that the i^{th} pair can decode its own PLNC signal. However, due to the imperfect SIC operation, SIC error is present in each of the successfully decoded pair [38]. Therefore, the i^{th} pair SINR can be expressed as [21]

$$\gamma_i^{\text{ipSIC}} = \frac{g_{i,j}\alpha_i P_r}{\sigma^2 + g_{i,j}\sum_{k=1}^{k=i-1} \alpha_k P_r + \omega_i \sum_{k=i+1}^{k=N} \alpha_k h_k P_r}. \quad (28)$$

where the superscript 'ipSIC' denote the imperfect SIC, denominator second term is the interference signal which comes from 1 to $(i-1)^{\text{th}}$ pairs, third term is the imperfect SIC errors and $\omega_i, 0 \leq \omega_i \leq 1$ is the imperfect SIC error coefficient of i^{th} pair. After SIC operation, third term is not part of the received signal hence the channel gain $|h_k|^2$ follows *iid* exponential distribution with parameter $\upsilon_h = 1/\mu_h$.

For i^{th} pair, SIC error occurs from $(i+1)^{\text{th}}$ to N^{th} pairs. Further, each successfully decoded pairs also experience its own SIC errors. Let $l \in ((i+1), \ldots N)$, then the SINR of l^{th} pair to decode i^{th} pair is given by

$$\gamma_{l\to i}^{\text{ipSIC}} \approx \frac{g_{i,j}\alpha_l P_r}{\sigma^2 + g_{i,j}\sum_{k=1}^{k=l-1} \alpha_k P_r + \omega_l \sum_{k=l+1}^{k=N} \alpha_k e_k P_r}. \quad (29)$$

Note at $l = N$, $\omega_l = 0$. Using (28) and (29), the outage probability of the i^{th} pair in the NOBC link can be expressed as [5]

$$p_{\text{out},N}^{\text{NOBC}}(R) = 1 - \underbrace{Pr(\gamma_{l\to i}^{\text{ipSIC}} > \gamma_4;\ \forall\, l \geq i+1,\ \gamma_i^{\text{ipSIC}} > \gamma_4)}_{\text{NOBC}}. \quad (30)$$

where $\gamma_4 = 2^{(N+1)R} - 1$ is the threshold SNR for end-to-end communication. By substituting the respective SINR expressions and then integrating, the outage probability of the i^{th} pair NOBC link can be determined as

$$p_{\text{out},N}^{\text{NOBC}}(R) = 1 - [G_2 e^{-\frac{\upsilon_x\gamma_4}{\beta^*}} \frac{\beta^*}{\upsilon_x\gamma_4 + \upsilon_m'\beta^*} - \frac{G_1 G_2}{\upsilon_m}\frac{1}{1+\xi}\frac{\beta^*}{\upsilon_m\beta_i + (\upsilon_x + \upsilon_m')\gamma_4} \times e^{-\frac{\gamma_4\upsilon_x}{\beta^*}} e^{-\upsilon_m(\frac{\beta_i}{\beta^*}-1)}]. \quad (31)$$

where $G_1 = \prod_{k=i+1}^{k=N} \upsilon_k \sum_{m=i+1}^{m=N} \frac{1}{\prod_{n=i+1 n\neq m}^{n=N}(\upsilon_n - \upsilon_m)}$ $G_2 = \prod_{k=i+2}^{k=N} \upsilon_k' \sum_{q=i+2}^{q=N} \frac{1}{\prod_{n=i+2 n\neq q}^{n=N}(\upsilon_n' - \upsilon_q')}$ $\beta_l = (\alpha_l\rho - \sum_{k=1}^{k=l-1}\alpha_k\rho\gamma_4)$ is the NOMA power splitting parameters of pairs $(i+1)$ to N and $\beta_i = (\alpha_i\rho - \sum_{k=1}^{k=i-1}\alpha_k\rho\gamma_4)$ for i^{th} pair, $\xi = \frac{\upsilon_m\beta_i}{\gamma_4\upsilon_x}$.

Proof: See Appendix B.

Proposition 1: In the event of $\beta_i > \beta^*$, the ratio $\frac{\upsilon_k}{\upsilon_m}\approx 1$ and $\frac{\upsilon_k'}{\upsilon_q'}\approx 1$, the outage probability of the i^{th} pair in the NOBC link can be simplified as

$$p_{\text{out,N}}^{\text{NOBC}}(R) \equiv 1 - e^{-\frac{\upsilon_x\gamma_4}{\beta^*}}[\frac{\beta^*}{\upsilon_x\gamma_4 + \upsilon_q'\beta^*} - \frac{1}{1+\xi}\sum_{q=i+2}^{q=N}\frac{\beta^*}{\upsilon_m\beta_i + (\upsilon_x + \upsilon_q')\gamma_4} \times (\sum_{m=i+1}^{m=N} e^{-\upsilon_m(\frac{\beta_i}{\beta^*}-1)})^N]. \quad (32)$$

Also in β_i and β^*, when the parameter $\rho \to \infty$, the diversity of the i^{th} pair will be negligible [19], i.e., $\lim_{x\to\infty}[e^{-x}]^N \equiv e^{-x} \approx 0$. Therefore, at $\beta_i = 2\beta^*$, the asymptotic outage probability of i^{th} pair in the NOBC link can be computed as,

$$p_{\text{out},N}^{\text{NOBC}}(R) \simeq 1 - e^{\left(-\frac{\upsilon_x\gamma_4}{\beta^*}\right)}[\frac{\beta^*}{\upsilon_x\gamma_4 + \upsilon_q'\beta^*} - \frac{1}{1+\xi}\sum_{q=i+2}^{q=N}\frac{\beta^*}{\upsilon_m\beta_i + (\upsilon_x + \upsilon_q')\gamma_4} \times \sum_{m=i+1}^{m=N} e^{-\upsilon_m}]. \quad (33)$$

By substituting (27) and (33) in (20), the end-to-end outage probability of the i^{th} pair in N-pair NOMA-PLNC wireless network can be obtained.

Similarly at $\omega_l = 0$, the outage probability of the l^{th} pair far user in NOBC link is expressed as

$$p_{\text{out},N}^{\text{far}}(R) = 1 - Pr(\gamma_l > \gamma_4). \quad (34)$$

By substituting γ_l, it can be written as

$$p_{\mathrm{out},N}^{\mathrm{far}}(R) = 1 - Pr((g_{l,j}(\alpha_l \rho - \sum_{k=1}^{k=l-1} \alpha_k \rho \gamma_4) > \gamma_4,). \quad (35)$$

Let $(\alpha_l - \sum_{k=1}^{k=l-1} \alpha_k \gamma_4) = \alpha_x$, then outage becomes

$$p_{\mathrm{out},N}^{\mathrm{far}}(R) = \int_0^{\frac{\gamma_4}{\alpha_x \rho}} f_{X_2}(x_2) dx_2. \quad (36)$$

where $f_{X_2}(x_2)$ is the probability density function (PDF) of $|g_{l,j}|^2$, after integrating and simplifying, the outage probability of the far user can be determined as

$$p_{\mathrm{out},N}^{\mathrm{far}}(R) = 1 - e^{\frac{\gamma_4}{(\alpha_{i+1} - \sum_{k=1}^{k=l-1} \alpha_k \gamma_4)\rho}}. \quad (37)$$

D. SECRECY OUTAGE PROBABILITY OF THE NEAR USER

In this section, secrecy outage probability of the proposed network is derived using the respective secrecy rates. Thus, the near user secrecy rate can be expressed as follows [35]

$$C_{\mathrm{secry,n}} = [C_{\mathrm{near}} - C_{\mathrm{Eve,\,n}}]^+. \quad (38)$$

where the symbol $[.]^+ = max(0, x)$, C_{near} is the near user capacity and C_{Eve} is the Eve capacity and they can be written as

$$C_{\mathrm{near}} = \log\left(1 + \frac{|g_{\mathrm{bn}}|^2 \alpha_i P_r}{|g_{\mathrm{LI}}|^2 P_{\mathrm{LI}} + \sigma^2}\right). \quad (39)$$

$$C_{\mathrm{Eve,\,n}} = \log\left(1 + \frac{|g_{\mathrm{be}}|^2 \alpha_i P_r}{|g_{\mathrm{ne}}|^2 P_{\mathrm{AN}} + \sigma^2}\right). \quad (40)$$

Using (39) and (40), the secrecy outage probability of the near user can be written as

$$p_{\mathrm{secry,n}}(R) = Pr([C_{\mathrm{near}} - C_{\mathrm{Eve,\,n}}] < R). \quad (41)$$

$$p_{\mathrm{secry,n}}(R) = Pr\left(\log \frac{1 + \gamma_{\mathrm{near}}}{1 + \gamma_{\mathrm{Eve,\,n}}} < R\right). \quad (42)$$

Further, the secrecy outage probability of the proposed network can be modified as

$$p_{\mathrm{secry,n}}(R) = Pr\left(\gamma_{\mathrm{near}} < 2^R(1 + \gamma_{\mathrm{Eve,\,n}}) - 1\right). \quad (43)$$

Let $\gamma_{\mathrm{near}} = x_3$ and $\gamma_{\mathrm{Eve,\,n}} = y_1$, then it can be written as

$$p_{\mathrm{secry,n}}(R) = \int_0^{\infty} Pr\left(x_3 < 2^R(1 + y_1) - 1\right) f_{Y_1}(y_1) dy_1. \quad (44)$$

where $f_{Y_1}(y_1)$ is the PDF of the eavesdropper SINR, $\gamma_{\mathrm{Eve,\,n}}$, then it can modified as

$$p_{\mathrm{secry,n}}(R) = \int_0^{\infty} \int_{-\infty}^{2^R(1+y_1)-1} f_{X_3}(x_3) f_{Y_1}(y_1) dx_3 dy_1. \quad (45)$$

By integrating the PDF of 'x3', the secrecy outage probability can be written as

$$p_{\mathrm{secry,n}}(R) = \int_0^{\infty} F_{X_3}(2^R(1 + y_1) - 1) f_{Y_1}(y_1) dy_1. \quad (46)$$

where $F_X(.)$ is the CDF of the near user SINR, γ_{near} and it can be expressed as

$$F_{X_3}(x_3) \approx \frac{\pi}{2N} \sum_{i=1}^{N} \Phi_i \left(1 - \frac{\alpha_i}{\alpha_i + v_{LI} \phi_i x_3} e^{-\frac{\phi_i x_3}{\alpha_i \mathrm{SNR}}}\right). \quad (47)$$

where $SNR = \frac{P_i}{\sigma^2}$, $\Phi_i = \sqrt{1 - \theta_i^2}(\theta_i + 1)$, $\theta_i = cos(\frac{2i-1}{2N}\pi)$, $\phi_i = 1 + (\frac{r_n}{2}(\theta_i + 1))^\alpha$.

Proof: See Appendix C.

The PDF of $f_{Y_1}(y_1)$ is given as

$$f_{Y_1}(y_1) = \left(\frac{\alpha_i D_{\mathrm{ne}} D_{\mathrm{be}}}{(\alpha_i D_{\mathrm{ne}} + y_1 D_{\mathrm{be}})^2} + \frac{D_{\mathrm{ne}} D_{\mathrm{be}}}{\mathrm{INR}(\alpha_i D_{\mathrm{ne}} + y_1 D_{\mathrm{be}})}\right) \times e^{-\frac{y_1 D_{\mathrm{be}}}{\alpha_i \mathrm{INR}}}. \quad (48)$$

where $\mathrm{INR} = \frac{P_{\mathrm{AN}}}{\sigma^2}$ is the Interference to noise ratio (INR), $D_{\mathrm{ne}} = 1 + d_{\mathrm{ne}}^\alpha$, $D_{\mathrm{be}} = 1 + d_{\mathrm{be}}^\alpha$.

Proof: See Appendix D.

By substituting the CDF and the PDF from (47) and (48) in (46), the secrecy outage probability of the near user can be computed which is given in (57), as shown at the bottom of the next page.

Proof: See Appendix E.

E. SECRECY OUTAGE PROBABILITY OF THE FAR USER

The secrecy outage probability of the far user can be written as

$$p_{\mathrm{secry,f}}(R) = Pr([C_{\mathrm{far}} - C_{\mathrm{Eve,f}}]^+ < R). \quad (49)$$

where C_{far} and $C_{\mathrm{Eve,f}}$ are far user and Eve with far user capacities respectively and they can be expressed as given below.

$$C_{\mathrm{far}} = log\left(1 + \frac{|g_{\mathrm{bf}}|^2 \alpha_{i+1} P_r}{|g_{\mathrm{bf}}|^2 \alpha_i P_r + |g_{\mathrm{LI}}|^2 P_{\mathrm{LI}} + \sigma^2}\right). \quad (50)$$

$$C_{\mathrm{Eve,f}} = log\left(1 + \frac{|g_{\mathrm{be}}|^2 \alpha_{i+1} P_r}{|g_{\mathrm{be}}|^2 \alpha_i P_r + |g_{\mathrm{fe}}|^2 P_{\mathrm{AN}} + \sigma^2}\right). \quad (51)$$

By substituting (50) and (51) into (49), the secrecy outage of the far user is simplified as

$$p_{\mathrm{secry,f}}(R) = Pr\left(\gamma_{\mathrm{far}} < 2^R(1 + \gamma_{\mathrm{Eve,f}}) - 1\right). \quad (52)$$

Let $\gamma_{\mathrm{far}} = x_4$ and $\gamma_{\mathrm{Eve,f}} = y_3$, then it can be written as

$$p_{\mathrm{secry,f}}(R) = \int_0^{\infty} Pr\left(x_4 < 2^R(1 + y_3) - 1\right) f_{Y_3}(y_3) dy_3. \quad (53)$$

where $f_{Y_3}(y_3)$ is the PDF of the Eve with far user SINR, $\gamma_{\mathrm{Eve,f}}$, then it can modified as

$$p_{\mathrm{secry,f}}(R) = \int_0^{\infty} \int_{-\infty}^{2^R(1+y_3)-1} f_{X_4}(x_4) f_{Y_3}(y_3) dx_4 dy_3. \quad (54)$$

where $\int_{-\infty}^{2^R(1+y_3)-1} f_{X_4}(x_4)dx_4 = F_{X_4}(x_4)$. Using (47), the CDF of x_4 is determined as

$$F_{X_4}(x_4) \approx \frac{\pi}{2M}\sum_{i=1}^{M}\Phi_i'\left(1-\frac{\alpha_i}{\alpha_i+\nu_{\text{LI}}\phi_i' x_4}e^{-\frac{\phi_i' x_4}{\alpha_i \text{SNR}}}\right). \quad (55)$$

where $\Phi_i' = \sqrt{1-\theta_i'^2}(\theta_i'+1)$, $\theta_i' = \cos(\frac{2i-1}{2M}\pi)$, $\phi_i' = 1+(\frac{r_f}{2}(\theta_i'+1))^{\alpha}$.

Using (48), the PDF $f_{Y_3}(y_3)$ is computed as given below.

$$f_{Y_3}(y_3) = \Big(\frac{(\alpha_{i+1}-\alpha_i R_{\text{th}})D_{\text{fe}}D_{\text{be}}}{((\alpha_{i+1}-\alpha_i R_{\text{th}})D_{\text{fe}}+y_3 D_{\text{be}})^2} + \frac{D_{\text{fe}}D_{\text{be}}}{\text{INR}((\alpha_{i+1}-\alpha_i R_{\text{th}})D_{\text{fe}}+y_3 D_{\text{be}})}\Big) e^{-\frac{y_3 D_{\text{be}}}{(\alpha_{i+1}-\alpha_i R_{\text{th}})\text{INR}}}. \quad (56)$$

where $D_{\text{fe}} = 1+d_{\text{fe}}^{\alpha}$, $\kappa' = (\nu_{\text{LI}}\phi_i' R_{\text{th}} - (\alpha_{i+1}-\alpha_i R_{\text{th}}) - \phi_i'\nu_{\text{LI}})$, $\chi_i' = \frac{\text{SNR}D_{\text{be}}+\text{INR}\phi i' R_{\text{th}}}{(\alpha_{i+1}-\alpha_i R_{\text{th}})\text{SNRINR}}$, $\eta_1' = \frac{(\alpha_{i+1}-\alpha_i R_{\text{th}})D_{\text{fe}}}{D_{\text{be}}}\chi_i'$, $\eta_2' = \frac{\phi_i' R_{\text{th}}+(\alpha_{i+1}-\alpha_i R_{\text{th}})-\phi_i'}{\phi_i' R_{\text{th}}}\chi_i'$. Finally, using (55) and (56) in (54), the secrecy outage probability of the far user is determined in (58), as shown at the bottom of the page.

IV. NUMERICAL RESULTS

In this section, the outage performance of the proposed N pair NOMA-PLNC wireless network is analyzed over uplink, downlink and end-to-end level. The uplink and downlink channel variances $\upsilon_{i,j}$ is considered as 1 and Gaussian-Laguerre parameter K is set to 50. In all the simulations, 20,000 monte-carlo iterations is used using Matlab software. Simulation parameters are listed in Table.1.

The outage performance of uplink PLNC network is shown in Figure 3. To know the impact of PLNC scheme, proposed PLNC network is compared with the network operating without PLNC scheme. Numerical results are validated using simulated results. In this simulation, the threshold data rate is considered as $R = 1$. From this figure, it is observed that the performance of the uplink PLNC network is significantly improved when compare to the non-PLNC network. Also, the outage performance of the network is analyzed when the users are operating with different frequency bands W_1 and W_2. For the target outage of 10^{-2}, the proposed PLNC network requires 31 *dB* SNR, whereas around 38 *dB* SNR used by the non-PLNC network which reflects the impact of the PLNC scheme in the cellular network.

Outage performance of downlink NOMA with different rates is shown in Figure 4. Near user and far user distances are taken as 3m and 6m respectively. Eve is not considered in this simulation. From this figure, it is observed that the impact of the interference in the far user is increase while increase the data rate. Therefore, the reliability of the far user is ensured by the allocated data rate. Figure 5 shows the outage performance of the proposed two pairs NOMA-PLNC network in uplink, downlink and end-to-end levels. Simulation results are presented to validate the numerical results.The PLNC scheme is used in the uplink and the NOMA scheme is used in the downlink. It is noted that downlink outage

TABLE 1. Simulation Parameters.

Symbol	Parameters	Value
α_i	Power allocation coefficient	0.7
α	Path loss exponent	2
ω_i	imperfect SIC	1
R	Threshold secrecy rates	0.1, 0.5, 1
d_{ne}	Distance from the near user to Eve	4m, 5m
d_{fe}	Distance from the far user to Eve	3m
r_n	Inner circle radius	5m
r_f	Outer circle radius	10m

$$p_{\text{secry,n}}(R) = \frac{\pi}{2N}\sum_{i=1}^{N}\Phi_i - \frac{\pi}{2N}\sum_{i=1}^{N}\frac{\Phi_i D_{\text{ne}}\chi_i^2\alpha_i^2}{D_{\text{be}}\phi_i R_{\text{th}}}e^{\left(-\frac{\phi_i R_{\text{th}}}{\alpha_i \text{SNR}}\right)}\sum_{k=1}^{K}\frac{\Omega_i}{(x_k+\eta_1)^2+(x_k+\eta_2)} - \frac{\pi}{2N}\sum_{i=1}^{N}\frac{\Phi_i D_{ne}D_{\text{be}}\alpha_i}{\text{INR}[\kappa D_{\text{be}}-\alpha_i D_{\text{ne}}\phi_i R_{\text{th}}]}e^{\left(-\frac{\phi_i R_{\text{th}}}{\alpha_i \text{SNR}}\right)}\left[(-e^{\eta_1})\text{Ei}(-\eta_1)+e^{\eta_2}\text{Ei}(-\eta_2)\right]. \quad (57)$$

$$p_{\text{secry,f}}(R) = \frac{\pi}{2M}\sum_{i=1}^{M}\Phi_i' - \frac{\pi}{2M}\sum_{i=1}^{M}\frac{\Phi_i' D_{\text{fe}}\chi_i'^2(\alpha_{i+1}-\alpha_i R_{\text{th}})^2}{D_{\text{be}}\phi_i' R_{\text{th}}}e^{\left(-\frac{\phi_i' R_{\text{th}}}{(\alpha_{i+1}-\alpha_i R_{\text{th}})\text{SNR}}\right)} \sum_{k=1}^{K}\frac{\Omega_i}{(x_k+\eta_1')^2+(x_k+\eta_2')} - \frac{\pi}{2M}\sum_{i=1}^{M}\frac{\Phi_i' D_{\text{fe}}D_{\text{be}}(\alpha_{i+1}-\alpha_i R_{\text{th}})}{\text{INR}[\kappa' D_{\text{be}}-(\alpha_{i+1}-\alpha_i R_{th})D_{\text{fe}}\phi_i' R_{\text{th}}]} e^{\left(-\frac{\phi_i' R_{\text{th}}}{(\alpha_{i+1}-\alpha_i R_{\text{th}})\text{SNR}}\right)}\left[(-e^{\eta_1'})\text{Ei}(-\eta_1')+e^{\eta_2'}\text{Ei}(-\eta_2')\right]. \quad (58)$$

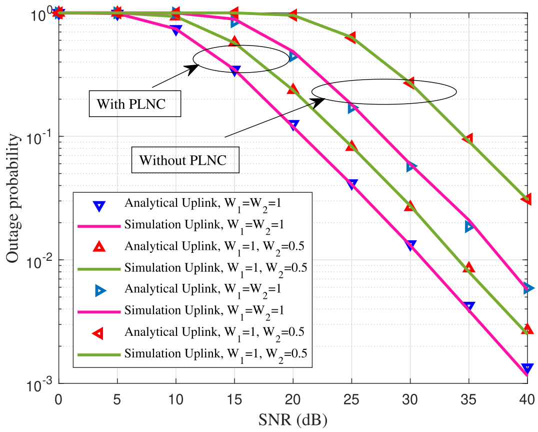

FIGURE 3. Outage probability of uplink NOMA with and without PLNC.

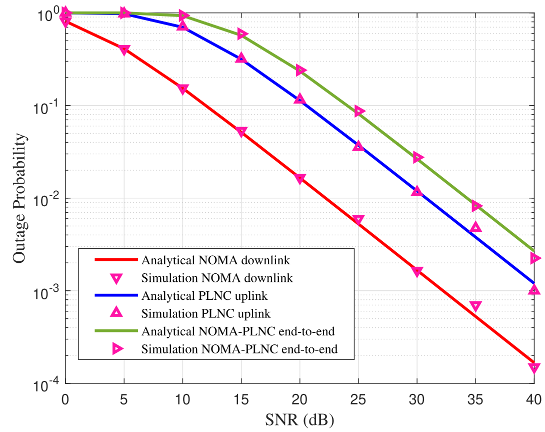

FIGURE 5. Uplink and downlink outage probability of two pairs NOMA-PLNC network.

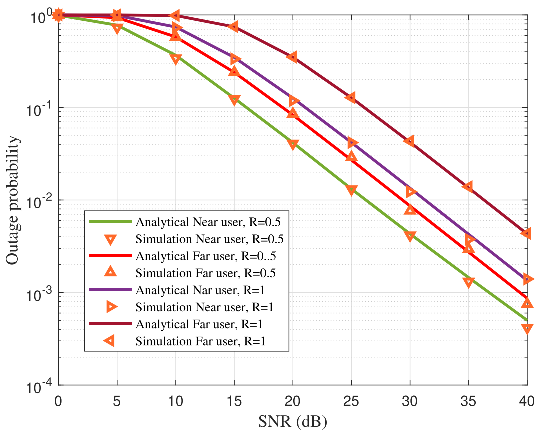

FIGURE 4. Outage probability of the downlink NOMA with different rates.

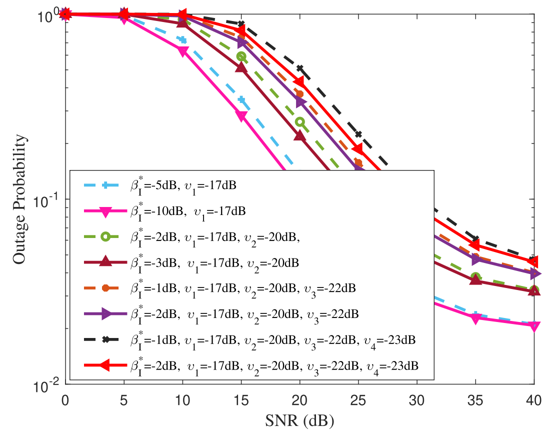

FIGURE 6. Outage probability of N-pair downlink NOMA with imperfect SIC interference's.

performance of the proposed two pair wireless network is improved dramatically than the uplink outage performance. Additionally, it is observed that the end-to-end outage performance of the proposed wireless network approaches nearly uplink performance because uplink outage is more dominant in this network.

Outage performance of downlink N pair NOMA of the proposed network is shown in Figure 6 with various interference levels. In this simulations, we varied inter-user interference's β_I^* and imperfect SIC interference's. From this figure, it is observed that the performance of the downlink of the proposed network is degraded gradually when the number of interference's increases. Also, the effect of the interference signal power is more at the high SNR regime of this proposed downlink. Similarly, the outage performance of the N pairs uplink of the proposed network is shown in Figure 7. The number of time slots considered in this simulations are 2, 3 and 4 to perform two users, three users and four users pairs respectively. It is noted that when the each user pair is added in the proposed network, then the base station require additional 5 dB SNR in this proposed NOMA-PLNC network.

Figure 8 shows the end-to-end outage performance of N-pair NOMA-PLNC network. In this simulation, a pair of user exchange their information within two time slots using PLNC scheme and for N-pair of users N+1 time slots used in that N time slots for the uplink and one time slot for the downlink are allocated to complete the overall communication. From this figure, it is noted that the proposed cellular network requires additional 5 dB SNR for every new pair included in the network at the target outage 10^{-2}. Similarly, the outage performance of the proposed network is analyzed with the imperfect SIC interference powers as shown in the Figure 9. In this simulations, four imperfect SIC interference's signals are considered. Also, at ω_i=0, the outage performance of the N pairs downlink NOMA network approaches to the ideal network performance.

The outage probability of downlink NOMA versus power allocation coefficient is shown in Figure 10. Although the coefficient $'\alpha_i'$ support the improvement of the outage performance of the proposed NOMA-PLNC wireless network, the effect of the interference signals are clearly exploited in this simulation. Thus, it gives the details about the allowable

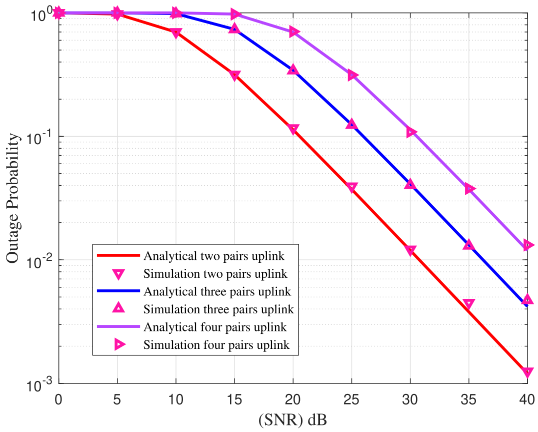

FIGURE 7. Outage probability of the N-pair uplink of the proposed network.

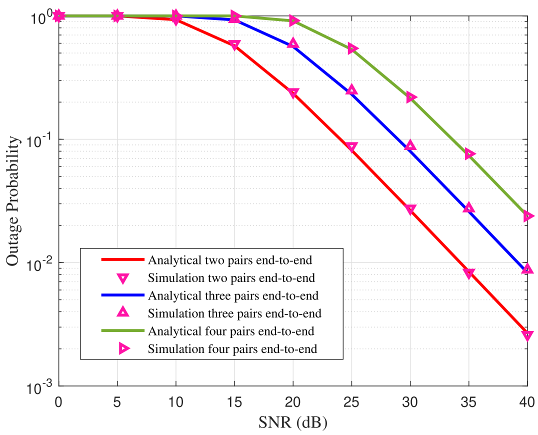

FIGURE 8. End-to-end outage probability of the proposed N-pair NOMA-PLNC wireless network.

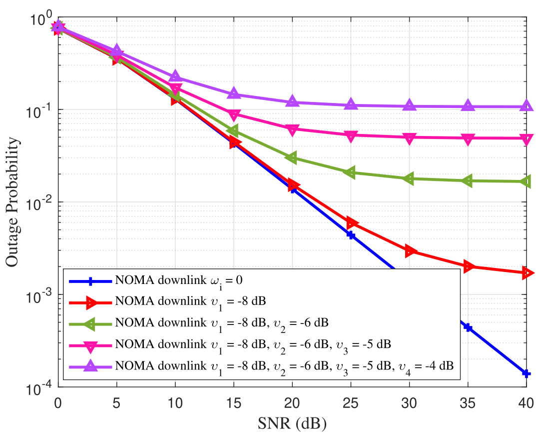

FIGURE 9. Outage probability of N-pairs downlink NOMA with perfect and imperfect SIC interference's.

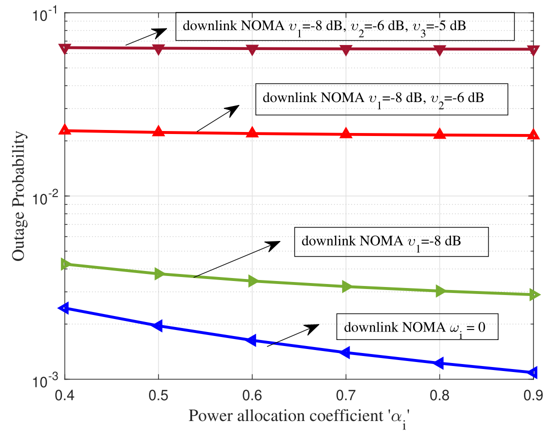

FIGURE 10. Outage probability of the N-pair downlink NOMA network with different power allocation coefficient.

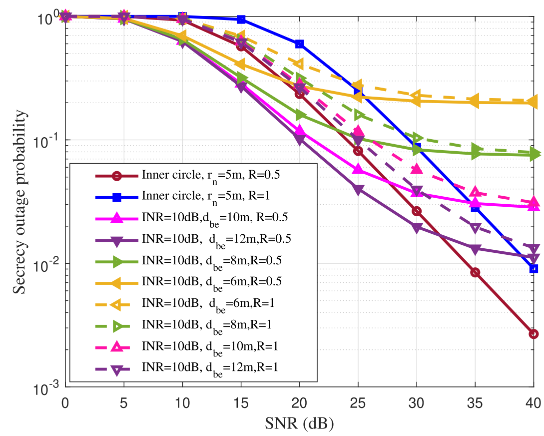

FIGURE 11. Secrecy outage probability of the downlink NOMA with different d_{be} values.

interference power level to the network designers to achieve the reliable connection.

Secrecy outage performance of downlink NOMA of the proposed network is shown in Figure 11. The following parameters are used in this simulation. Distance from near user to Eve, d_{ne} is set to 4m, the LI channel gain is $v_{\text{LI}} = -10dB$ and INR is fixed at 10 dB and inner circle radius is 5m. In this simulation, target secrecy rate fixed at $R = 1$ and $R = 0.5$ [12]. From this figure, it is observed that the effect of LI power and AN signal power are reflected in the downlink of the near user. Hence, the reliable connection is possible only with limited secrecy rates. Also, it is noted that the distance from the base station to Eve and from the Eve to the near user are the key factors which tolerate the network secrecy outage. Secrecy outage of the near user and far user are compared in Figure 12. Distances of the near user and far user are set to 4m and 7m respectively, INR is 10 dB, d_{ne} is 5m and d_{fe} is 3m. It is noted that error floor region to the far user starts from 0.05 to 1 whereas to the near user it is from 0.01 to 1 for 30 dB SNR. However, reliable communication of the users with allowable error floor is obtained based on the required secrecy rates.

Figure 13 shows the secrecy outage probability of the proposed network with different inner circle values.

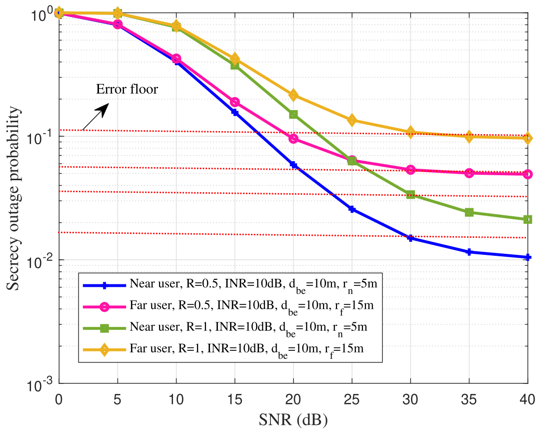

FIGURE 12. Secrecy outage probability of the downlink NOMA with different secrecy rates.

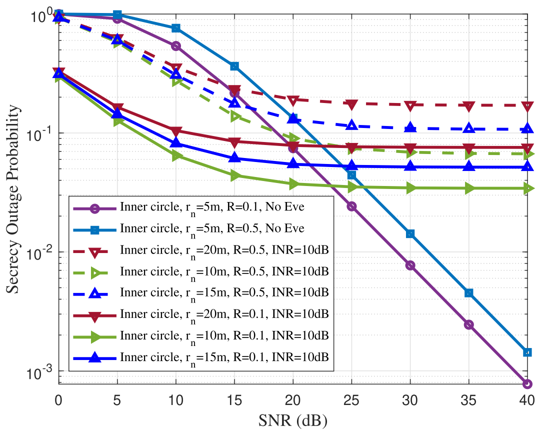

FIGURE 13. Secrecy outage probability of the downlink NOMA with different inner circle radius values.

The following simulation parameters are used in this simulation. The secrecy rates of the downlink near users are fixed at $R = 0.1$ and $R = 0.5$, the distance from the near user to Eve is set at $d_{\text{ne}} = 4m$ and the distance from the base station to Eve is set at $d_{\text{be}} = 10m$, LI channel gain is $v_{\text{LI}} = -10dB$ and INR value is $10dB$. It is noted that the secrecy outage of the near user downlink is increases proportional to the inner circle radius because the path loss increase. However, it is clear from this figure that Eve power is more dominant which makes the network performance worse.

V. CONCLUSION

In this paper, the outage performance of a proposed N-pair NOMA-PLNC network is analyzed in the presence of the Eve. Further, the impact of the PLNC scheme is studied in this proposed network. Closed form expressions for the uplink, downlink, end-to-end and N-pair end-to-end outage probability of the proposed N-pair NOMA-PLNC network is derived. Physical layer security is applied in this proposed model to address the security issues in the wireless environment. Full-duplex mode is employed in this network to send an AN signal to the Eve. Closed form expression for the secrecy outage probability of the proposed network is derived in the downlink level. Outage performance of the proposed network is compared with non-PLNC wireless network. Numerical results conclude the importance of PLNC scheme in the N-pair NOMA wireless network and the effect of imperfect SIC. Further, it shows that the proposed NOMA-PLNC wireless network achieves better performance when compared to the non-PLNC based NOMA wireless network.

APPENDIX A

The outage probability of the far user can be expressed as

$$p_{\text{out}}^{\text{far}}(R) = Pr(\text{NOBC link} < \gamma_2). \tag{A-1}$$

By substituting (16), it can be rewritten as

$$p_{\text{out}}^{\text{far}}(R) = Pr((\alpha_1\rho - \alpha_2\rho\gamma_2)|g_{i,j}|^2 < \gamma_2). \tag{A-2}$$

Let $\Psi = \frac{\gamma_2}{\rho(\alpha_1-\alpha_2\gamma_2)}$. By substituting the pdf of $|g_{i,j}|^2 = x_1$, it becomes

$$p_{\text{out}}^{\text{far}}(R) = \int_0^{\Psi} f_{X_1}(x_1)dx_1. \tag{A-3}$$

After simplifications, the outage probability of the far user is computed as

$$p_{\text{out}}^{\text{far}}(R) = 1 - e^{-\frac{\gamma_2}{\rho(\alpha_1-\alpha_2\gamma_2)\upsilon_{i,j}}}. \tag{A-4}$$

Using (17) and (A-4), the end-to-end outage probability of the two pairs hybrid NOMA-PLNC network can be determined which is given in (22).

APPENDIX B

The outage probability of the i^{th} pair in the NOBC link is given by

$$p_{\text{out},N}^{\text{NOBC}}(R) = 1 - \underbrace{Pr(\gamma_{l\to i}^{\text{ipSIC}} > \gamma_4;\ \forall\, l \geq i+1,\ \gamma_i^{\text{ipSIC}} > \gamma_4)}_{\text{NOBC}}. \tag{B-1}$$

Note that i^{th} pair decode its message only after successfully decoding of $(i+1)^{\text{th}}$ to N^{th} pair signals hence we need to consider success probability of the $(i+1)^{\text{th}}$ to N^{th} pairs. By expanding (B-1), we can written as

$$p_{\text{out},N}^{\text{NOBC}}(R) = 1 - Pr(\gamma_{i+1\to i}^{\text{ipSIC}} > \gamma_4 \cap \ldots \cap \gamma_{N\to i}^{\text{ipSIC}} > \gamma_4,\ \gamma_i^{\text{ipSIC}} > \gamma_4). \tag{B-2}$$

By substituting (28) and (29) in (B-2), the success probability of the NOBC link i^{th} pair can be rewritten as

$$\text{NOBC} = Pr((g_{i,j}(\alpha_{i+1}\rho - \sum_{k=1}^{k=i} \alpha_k\rho\gamma_4)$$

$$> \gamma_4(\omega_{i+1}\sum_{k=i+2}^{k=N} e_k\alpha_k\rho + 1)\cap\dots$$

$$\cap\ g_{i,j}(\alpha_N\rho - \sum_{k=1}^{k=N-1}\alpha_k\rho\gamma_4) > \gamma_4$$

$$g_{i,j}(\alpha_i\rho - \sum_{k=1}^{k=i-1}\alpha_k\rho\gamma_4)$$

$$> \gamma_4(\omega_i\sum_{k=i+1}^{k=N} h_k\alpha_k\rho + 1)). \quad \text{(B-3)}$$

Note that no SIC error for the N^{th} pair, let $\sum_{k=i+1}^{k=N} h_k = z_i$, $\sum_{k=i+2}^{k=N} e_k = z_{i+1}$, $\beta_l = (\alpha_l\rho - \sum_{k=1}^{k=l-1}\alpha_k\rho\gamma_4); l \in (i+1,\dots,N)$ and $\beta_i = (\alpha_i\rho - \sum_{k=1}^{k=i-1}\alpha_k\rho\gamma_4)$ are the NOMA power splitting parameters, $\alpha_l\rho > \sum_{k=1}^{k=l-1}\alpha_k\rho\gamma_4$ and $\alpha_i\rho > \sum_{k=1}^{k=i-1}\alpha_k\rho\gamma_4$. Let $g_{i,j} = x$, then the NOBC term can be rewritten as

$$\text{NOBC} = Pr(x > \gamma_4(\omega_{i+1}z_{i+1} + 1)/\beta_{i+1}\cap\dots$$

$$\cap x > \gamma_4/\beta_N, z_i < (\frac{x\beta_i}{\gamma_4} - 1)/\omega_i). \quad \text{(B-4)}$$

Let $\beta^* = \max(\beta_{i+1},\dots,\beta_N)$, $z^* = \max(\omega_{i+1}z_{i+1},\dots,\omega_{N-1}z_{N-1})$, $\beta_I^* = \max(\sum_{k=1}^{k=i}\alpha_k\rho\gamma_4,\dots,\sum_{k=1}^{k=N-1}\alpha_k\rho\gamma_4)$ is the inter-user interference's and $\omega_i = 1$, then the i^{th} pair outage can be simplified as [5]

$$\text{NOBC} = Pr(x > (\gamma_4(z^* + 1)/\beta^*), z_i < \frac{x\beta_i}{\gamma_4} - 1). \quad \text{(B-5)}$$

where z_i is the sum of independent random variables, z^* is maximum of random variables $(z_{i+1},..,z_{N-1})$, since $(z_{i+1} > z_{i+2} > \dots > z_{N-1})$, the maximum of $(z_{i+1},..,z_{N-1})$ is z_{i+1} and both are following the exponential distribution with parameters $\upsilon_m = 1/\mu_m$, $m = (i+1, i+2,\dots,N)$ and $\upsilon'_n = 1/\mu'_n$, $n = (i+2, i+3,\dots,N)$ respectively, x follows the exponential distribution with parameter $\upsilon_x = 1/\mu_x$. The PDF of z_i is given by [31]

$$f_{Z_i}(z_i) = \prod_{k=i+1}^{N}\upsilon_k\sum_{m=i+1}^{N}\frac{e^{-\upsilon_m z_i}}{\prod_{n=i+1,\, n\neq m}^{n=N}(\upsilon_n - \upsilon_m)}. \quad \text{(B-6)}$$

Similarly, the PDF of z^* is derived. Using the PDFs of x, z^* and z_i, the success probability of the N pairs NOBC link can be written as

$$\text{NOBC} = \int_0^\infty\int_{(\frac{\gamma_4(z^*+1)}{\beta^*})}^\infty\int_0^{\frac{x\beta_i}{\gamma_4}-1} f_X(x)f_{Z^*}(z^*)f_{Z_i}(z_i)\, dxdz^*dz_i. \quad \text{(B-7)}$$

By substituting the PDF of z_i and then integrating, the outage probability of the i^{th} pair becomes

$$\text{NOBC} = \int_0^\infty\int_{(\frac{\gamma_4(z^*+1)}{\beta^*})}^\infty [1 - \frac{G_1}{\upsilon_m}e^{\frac{-\upsilon_m x\beta_i}{\gamma_4}}e^{\upsilon_m}]\, f_X(x)f_{Z^*}(z^*)dxdz^*. \quad \text{(B-8)}$$

where $G_1 = \prod_{k=i+1}^{k=N}\upsilon_k\sum_{m=i+1}^{m=N}\frac{1}{\prod_{n=i+1 n\neq m}^{n=N}(\upsilon_n - \upsilon_m)}$

Then, by substituting the PDF of x, i^{th} pair outage can be written as

$$\text{NOBC} = \int_0^\infty\int_{(\frac{\gamma_4(z^*+1)}{\beta^*})}^\infty [\upsilon_x e^{-x\upsilon_x} - \frac{G_1\upsilon_x}{\upsilon_m} e^{-x(\frac{\upsilon_m\beta_i}{\gamma_4}+\upsilon_x)}e^{\upsilon_m}]f_{Z^*}(z^*)dz^*dx. \quad \text{(B-9)}$$

After integrating with respect to x, it can be simplified as

$$\text{NOBC} = \int_0^\infty [e^{-\frac{\upsilon_x\gamma_4(z^*+1)}{\beta^*}} - \frac{G_1}{\upsilon_m}e^{\upsilon_m}\frac{\gamma_4\upsilon_x}{\gamma_4\upsilon_x + \upsilon_m\beta_i} e^{-\frac{\gamma_4(z^*+1)}{\beta^*}(\frac{\upsilon_m\beta_i}{\gamma_4}+\upsilon_x)}]f_{Z^*}(z^*)dz^*. \quad \text{(B-10)}$$

Let $\xi = \frac{\upsilon_m\beta_i}{\gamma_4\upsilon_x}$ and integrate over z^*, then it becomes

$$\text{NOBC} = [G_2 e^{-\frac{\upsilon_x\gamma_4}{\beta^*}}\frac{\beta^*}{\upsilon_x\gamma_4 + \upsilon'_m\beta^*} - \frac{G_1G_2}{\upsilon_m}\frac{1}{1+\xi}\frac{\beta^*}{\upsilon_m\beta_i + (\upsilon_x + \upsilon'_m)\gamma_4} \times e^{-\frac{\gamma_4\upsilon_x}{\beta^*}}e^{-\upsilon_m(\frac{\beta_i}{\beta^*}-1)}]. \quad \text{(B-11)}$$

where $G_2 = \prod_{k=i+2}^{k=N}\upsilon'_k\sum_{q=i+2}^{q=N}\frac{1}{\prod_{n=i+2 n\neq q}^{n=N}(\upsilon'_n - \upsilon'_q)}$

Finally, the outage probability of the i^{th} pair in the NOBC link can be determined as

$$p_{\text{out},N}^{\text{NOBC}}(R) = 1 - [G_2 e^{-\frac{\upsilon_x\gamma_4}{\beta^*}}\frac{\beta^*}{\upsilon_x\gamma_4 + \upsilon'_m\beta_i} - \frac{G_1G_2}{\upsilon_m}\frac{1}{1+\xi}\frac{\beta^*}{\upsilon_m\beta_i + (\upsilon_x + \upsilon'_m)\gamma_4} \times e^{-\frac{\gamma_4\upsilon_x}{\beta^*}}e^{-\upsilon_m(\frac{\beta_i}{\beta^*}-1)}]. \quad \text{(B-12)}$$

APPENDIX C

A. CDF CALCULATION OF THE NEAR USER

In the inner circle region, there are N near users are distributed randomly and using HPPP, the i^{th} near user outage can be computed as given by

$$p_{\text{out}}^{\text{near}}(R) = Pr(\frac{|g_{\text{bn}}|^2\,\alpha_i P_r}{|g_{\text{LI}}|^2\,P_{\text{LI}} + \sigma^2} < R_{\text{th}}). \tag{C-1}$$

where $R_{\text{th}} = 2^R - 1$ is the threshold SNR, let $|g_{\text{bn}}|^2 = \frac{|g_{i,j}|^2}{1+d_{\text{bn}}^{\alpha}} = x_3$, $y_1 = |g_{\text{LI}}|^2$, then it can be written as

$$p_{\text{out}}^{\text{near}}(R) = \int_0^{\infty} Pr\left(x_3 < \frac{R_{\text{th}}(y_1 P_{\text{LI}} + \sigma^2)}{\alpha_i P_r}\right) f_{Y_1}(y_1)dy_1. \tag{C-2}$$

$$p_{\text{out}}^{\text{near}}(R) = \int_0^{\infty}\int_{-\infty}^{R''_{\text{th}}} f_{X_3}(x_3) f_{Y_1}(y_1)dx_3dy_1. \tag{C-3}$$

where $R''_{\text{th}} = \frac{R_{\text{th}}(y_1 P_{\text{LI}}+\sigma^2)}{\alpha_i P_r}$. Using HPPP, NOMA users are modeled as *iid* points in the inner circle region denoted as $d_{\text{bn}} = z_1$ and its PDF is given as

$$f_{Z_1}(z_1) = \frac{1}{\pi r_n^2}. \tag{C-4}$$

Then CDF of 'x_3' can be written as [32]

$$F_{X_3}(x_3) = \oint (1 - e^{(1+z_1^{\alpha})x_3}) f_{Z_1}(z_1)dz_1. \tag{C-5}$$

$$F_{X_3}(x_3) = \frac{2}{r_n^2}\int_0^{r_n} (1 - e^{(1+z_1^{\alpha})x_3})dz_1. \tag{C-6}$$

Using Gaussian-Chebyshev quadrature [33], it can be simplified as

$$F_{X_3}(x_3) \approx \frac{\pi}{2N}\sum_{i=1}^{N}\sqrt{(1-\theta_i^2)}(\theta_i+1)(1 - e^{(1+\phi_i)x_3}). \tag{C-7}$$

By substituting (C-7) and $f_{Y_1}(y_1)$ in (C-3), the outage probability of near user can be computed as

$$p_{\text{out}}^{\text{near}}(R) \approx \frac{\pi}{2N}\sum_{i=1}^{N}\Phi_i(1 - \frac{\alpha_i}{\alpha_i + v_{\text{LI}}\phi_i R_{th}} e^{-\frac{\phi_i R_{th}}{\alpha_i SNR}}). \tag{C-8}$$

APPENDIX D

B. PDF CALCULATION OF THE EVE

The CDF of the Eve with respect to near user can be expressed as

$$F_{Y_1}(y_1) = Pr\left(\frac{|g_{\text{be}}|^2\,\alpha_i P_r}{|g_{\text{ne}}|^2\,P_{\text{AN}} + \sigma^2} < R_{\text{th}}\right). \tag{D-1}$$

Let $y_1 = |g_{be}|^2$, $y_2 = |g_{ne}|^2$ follows the exponential distributions, then it can be written as

$$F_{Y_1}(y_1) = \int_0^{\infty} Pr\left(y_1 < \frac{R_{\text{th}}(y_2 P_{\text{AN}} + \sigma^2))}{\alpha_i P_r}\right) f_{Y_2}(y_2)dy_2. \tag{D-2}$$

To simplify the expression, let $\frac{R_{\text{th}}(y_2 P_{\text{AN}}+\sigma^2)}{\alpha_i P_r} = R'_{\text{th2}}$, then it becomes

$$F_{Y_1}(y_1) = \int_0^{\infty}\int_{-\infty}^{R'_{th2}} f_{Y_1}(y_1) f_{Y_2}(y_2)dy_1dy_2. \tag{D-3}$$

$$F_{Y_1}(y_1) = \int_0^{\infty}\left(1 - e^{-R'_{\text{th2}}}\right)e^{-y_2}dy_2. \tag{D-4}$$

After some mathematical manipulation, the CDF of the Eve with respect to near user can be computed as

$$F_{Y_1}(y_1) = 1 - \frac{\alpha_i D_{\text{ne}}}{\alpha_i D_{\text{ne}} + y_1 D_{\text{be}}} e^{-\frac{y_1 D_{\text{be}}}{\alpha_i \text{INR}}}. \tag{D-5}$$

By differentiating (D-5) with respect to 'y_1', the PDF of the Eve can be determined and it is given in (48).

Similarly, the CDF of the Eve with respect to far user can be written as

$$F_{Y_3}(y_3) = Pr\left(\frac{|g_{\text{be}}|^2\,\alpha_{i+1} P_r}{|g_{\text{be}}|^2\,\alpha_i P_r + |g_{\text{fe}}|^2\,P_{\text{AN}} + \sigma^2} < R_{\text{th}}\right). \tag{D-6}$$

By rearranging (D-6), the Eve outage with respect to far user can be written as

$$F_{Y_3}(y_3) = Pr\left(|g_{\text{be}}|^2 < \frac{(|g_{\text{fe}}|^2\,P_{\text{AN}} + \sigma^2)}{(\alpha_{i+1} - \alpha_i R_{\text{th}})P_r}\right). \tag{D-7}$$

Let $(\alpha_{i+1} - \alpha_i R_{th}) = \alpha_{\text{diff}}$, $y_3 = |g_{\text{be}}|^2$, $y_4 = |g_{\text{fe}}|^2$.

$$F_{Y_3}(y_3) = \int_0^{\infty} Pr\left(y_3 < \frac{R_{\text{th}}(y_4 P_{\text{AN}} + \sigma^2))}{\alpha_{\text{diff}} P_r}\right) f_{Y_4}(y_4)dy_4. \tag{D-8}$$

After integrating, the simplified expression of the CDF of Eve with respect to far user can be obtained as

$$F_{Y_3}(y_3) = 1 - \frac{\alpha_{\text{diff}} D_{\text{fe}}}{\alpha_{\text{diff}} D_{\text{fe}} + y_3 D_{\text{be}}} e^{-\frac{y_3 D_{\text{be}}}{\alpha_{\text{diff}}\text{INR}}}. \tag{D-9}$$

By differentiating $F_{Y_3}(y_3)$ with respect to 'y_3', the PDF of Eve with far user is obtained which is given in (56).

APPENDIX E

By substituting (55) and (56) in (54), the secrecy outage probability of the near user can be expressed by

$$p_{\text{secry,n}}(R) = \frac{\pi}{2N}\sum_{i=1}^{N}\Phi_i \int_0^{\infty}(1 - \frac{\alpha_i}{\alpha_i + v_{\text{LI}}\phi_i(2^R(1+y)-1)} e^{-\frac{\phi_i(2^R(1+y)-1)}{\alpha_i \text{SNR}}}) \left(\frac{\alpha_i D_{\text{ne}} D_{\text{be}}}{(\alpha_i D_{\text{ne}} + y D_{\text{be}})^2} + \frac{D_{\text{ne}} D_{\text{be}}}{\text{INR}(\alpha_i D_{\text{ne}} + y D_{\text{be}})}\right) e^{-\frac{y D_{\text{be}}}{\alpha_i \text{INR}}}dy. \tag{E-1}$$

The secrecy outage probability is separated into four terms.

$$p_{\text{secry,n}}(R) = B(A_1 + A_2 + A_3 + A_4). \tag{E-2}$$

where $B = \frac{\pi}{2N}\sum_{i=1}^{N}\Phi_i$.

$$A_1 = \int_0^{\infty}\frac{\alpha_i D_{\text{ne}} D_{\text{be}}}{(\alpha_i D_{\text{ne}} + y D_{\text{be}})^2} e^{-\frac{y D_{\text{be}}}{\alpha_i \text{INR}}}dy. \tag{E-3}$$

$$A_2 = \int_0^{\infty}\frac{D_{\text{ne}} D_{\text{be}}}{\text{INR}(\alpha_i D_{\text{ne}} + y D_{\text{be}})} e^{-\frac{y D_{\text{be}}}{\alpha_i \text{INR}}}dy. \tag{E-4}$$

TABLE 2. List of Symbols.

Symbol	Parameter
υ	channel variance
σ^2	noise variance
α_i	power allocation coefficient
α	path loss exponent
$\gamma_1, \gamma_2, \gamma_3$ and γ_4	threshold SNR's
ρ	SNR of each user
ω	imperfect SIC
Ei(.)	Exponential integral
$\mathbb{E}(.)$	Expectation operator

TABLE 3. List of Acronyms.

Acronym	Full form
5G	fifth generation
6G	sixth generation
3GPP	third generation partnership project
AN	artificial noise
AWGN	additive white Gaussian noise
BER	bit error rate
BPSK	binary phase shift keying
CDF	cumulative distribution function
CSI	channel state information
DF	decode and forward
Eve	Eavesdropper
FD	full duplex
HPPP	homogeneous Poisson point process
INR	interference to noise ratio
LI	loop interference
LMS	land mobile satellite
mMTC	massive machine type communication
MMSE	minimum mean square error
NOMA	non orthogonal multiple access
NOBC	non orthogonal broadcast channel
OFDMA	orthogonal frequency division multiple access
OMAC	orthogonal multiple access channel
PLNC	physical layer network coding
PN	pseudo noise
SC	superposition coding
SIC	successive interference cancellation
SINR	signal to interference plus noise ratio
SNR	signal to noise ratio

$$A_3 = -\int_0^\infty \frac{\alpha_i}{\text{INR}(\alpha_i D_{\text{ne}} + yD_{\text{be}}) + (\alpha_i + \nu_{\text{LI}}\phi_i R^{''}_{\text{th3}})} e^{-\frac{\phi_i(2^R(1+y)-1)}{\alpha_i \text{SNR}}} e^{-\frac{yD_{\text{be}}}{\alpha_i \text{INR}}}. \quad \text{(E-5)}$$

where $R^{''}_{th3} = (2^R(1+y)-1)$.

$$A_4 = -\int_0^\infty \frac{\alpha_i^2}{(\alpha_i D_{\text{ne}} + yD_{\text{be}})^2 + (\alpha_i + \nu_{\text{LI}}\phi_i R^{''}_{\text{th3}})} e^{-\frac{\phi_i R^{''}_{\text{th}}}{\alpha_i \text{SNR}}} e^{-\frac{yD_{\text{be}}}{\alpha_i \text{INR}}}. \quad \text{(E-6)}$$

Using [[34], (3.353.3) and (3.352.4)], A_1 and A_2 can be determined as

$$A_1 = \frac{1}{\text{INR}D_{\text{be}}} e^{\frac{D_{\text{ne}}}{\text{INR}}} \text{Ei}\left(-\frac{D_{\text{ne}}}{\text{INR}}\right) + \frac{1}{D_{\text{ne}}D_{\text{be}}}. \quad \text{(E-7)}$$

$$A_2 = -\frac{1}{\text{INR}D_{\text{be}}} e^{\frac{D_{\text{ne}}}{\text{INR}}} \text{Ei}\left(-\frac{D_{\text{ne}}}{\text{INR}}\right). \quad \text{(E-8)}$$

Using [[34], (3.352.4)], A_3 can be simplified as

$$A_3 = \frac{\alpha_i}{\text{INR}[\kappa D_{\text{be}} - \alpha_i D_{\text{ne}} \phi_i \nu_{\text{LI}} R_{\text{th}}]} e^{-\frac{\phi_i(2^R-1)}{\alpha_i \text{INR}}} \times [-e^{\eta_1}\text{Ei}(-\eta_1) + e^{\eta_2}\text{Ei}(-\eta_2)]. \quad \text{(E-9)}$$

where Ei(.) is the exponential integral function, $\kappa = (\nu_{LI}\phi_i R_{\text{th}} - \alpha_i - \phi_i \nu_{\text{LI}})$, $\chi_i = \frac{\text{SNR}D_{\text{be}} + \text{INR}\phi i R_{\text{th}}}{\alpha_i \text{SNRINR}}$, $\eta_1 = \frac{\alpha_i D_{\text{ne}}}{D_{\text{be}}}\chi_i$, $\eta_2 = \frac{\phi_i R_{\text{th}} + \alpha_i - \phi_i}{\phi_i R_{\text{th}}}\chi_i$, $\Omega_i = \frac{(K!)^2}{[L'_K(x_i)]^2 x_i}$, in Ω_i, $L'_K(x_i)$ is first derivatives of polynomial, $L_K(x) = e^x \frac{d^k}{dx^K}(x^K e^{-x})$ and x_i is the zero point of $L_K(x)$. Integral in A_4 is in the form $\int_0^\infty \frac{e^{-x}}{(a+x)^2(b+x)}$ (a and b constants), hence using Gaussian-Laguerre quadrature [34] it can be simplified as

$$A_4 = \frac{\Phi_i D_{\text{ne}} \chi_i^2 \alpha_i^2}{D_{\text{be}} \phi_i \nu_{\text{LI}} R_{\text{th}}} \exp\left(-\frac{\phi_i(2^R-1)}{\alpha_i \text{SNR}}\right) \sum_{k=1}^{K} \frac{\Omega_i}{(x_k+\eta_1)^2 + (x_k+\eta_2)}. \quad \text{(E-10)}$$

By substituting B, A1, A2, A3, A4 in (E-2), secrecy outage probability of the near user is obtained which is given in (57).

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SAMIKKANNU RAJKUMAR (Member, IEEE) received the B.E. degree in electronics and communication engineering from the Angala Amman College of Engineering and Technology, Tamil Nadu, India, in 2000, the M.E. degree in communication systems from the Thiagarajar College of Engineering, Tamil Nadu, in 2006, and the Ph.D. degree in wireless communication from Anna University, Chennai, India, in 2015. Currently, he is a Postdoctoral Researcher with the Centre for Telecommunication Research, Sri Lanka Technological Campus, Padukka, Sri Lanka. He has published several refereed papers in various international journals and conferences. His current research interests include non-orthogonal multiple access technique, physical layer security, visible light communication, and soft information relay.

DUSHANTHA NALIN K. JAYAKODY (Senior Member, IEEE) received the M.Sc. degree in electronics and communications engineering from Eastern Mediterranean University, Turkey (under the University Full Graduate Scholarship), and the Ph.D. degree in electronics and communications engineering from the University College Dublin, Ireland.

From 2014 to 2016, he was a Postdoctoral Research Fellow at the University of Tartu, Estonia, and the University of Bergen, Norway. From 2016 to 2022, he was a Professor at the School of Computer Science and Robotics, National Research Tomsk Polytechnic University (TPU), Russia. He held visiting and/or sabbatical positions at the Center for Telecommunications Research, University of Sydney, Australia, in 2015, and Texas A & M University, in 2018. He was a Visiting Professor within the framework of the Academy of Finland at the University of Jyvaskyla, Finland, in 2019 and 2022. He was also a Visiting Professor at the University of Juiz de Fora, Brazil, in 2019. Since 2022, he has been with the COPELABS, Lusófona University, Lisbon, Portugal. He is the Head of the School of Postgraduate Studies and Research, Sri Lanka Technological Campus (SLTC), Padukka, Sri Lanka, and has been the Founding Head of the Centre of Telecommunication Research, SLTC, since January 2019. He is supervising/supervised 15 Ph.D. students and many master's and undergraduate students and five Postdoctoral researchers. Since 2019, he has been a Resource Person/Visiting Professor for the Department of Electronics and Communication Engineering, National Institute of Tiruchirappalli, India, within the SPARC Project of the Ministry of Human Resources in India. He has published nearly 200 international peer-reviewed journals and conference papers and books. He has attracted nearly U.S. $6 million research funding from many international grant agencies such as European Commission, Russian Science Foundation, and the Ministry of Human Resource India. His research interests include PHY and NET layer prospective of 5G communications technologies, such as NOMA for 5G, cooperative wireless communications, device to device communications, LDPC codes, and unmanned aerial vehicle.

Prof. Jayakody is a fellow of IET. He has organized or co-organized more than 30 workshops, special sessions, and IEEE conferences. He was a recipient of the Best Paper Award from the International Conference on Communication, Management and Information Technology (ICCMIT), in 2017, and from the International Conference on Emerging Technologies of Information and Communications, Bhutan, in March 2019. He received the Education Leadership Award from the World Academic Congress, in 2019; and the Outstanding Faculty Award from National Research Tomsk Polytechnic University, Russia, in 2017 and 2018; the Distinguished Researcher in Wireless Communications Award, Chennai, in 2019; the Best Publication Award from the Sri Lanka Technological Campus, in 2019 and 2020; and the Presidential Award for outstanding research performance in the year 2021. He serves on the Advisory Board for *MDPI Multidisciplinary Journal Sci*. He also serves as a reviewer for various IEEE TRANSACTIONS and other journals. He is currently an Area Editor of the *Elsevier Physical Communications Journal*, *MDPI Information Journal*, *MDPI Sensors*, and *Wiley Internet of Technology Letters*.

REEM ALKANHEL (Member, IEEE) received the B.S. degree in computer sciences from King Saud University, Riyadh, Saudi Arabia, in 1996, the M.S. degree in information technology (computer networks and information security) from the Queensland University of Technology, Brisbane, Australia, in 2007, and the Ph.D. degree in information technology (networks and communication systems) from Plymouth University, Plymouth, U.K., in 2019. She has been with Princess Nourah bint Abdulrahman University, Riyadh, since 1997, where she is currently an Assistant Professor with the College of Computer and Information Sciences. Her current research interests include communication systems, networking, the Internet of Things, software-defined networking, and information security.

AMMAR MUTHANNA (Senior Member, IEEE) received the B.Sc., M.Sc., and Ph.D. degrees from the Saint-Petersburg State University of Telecommunications, in 2009, 2011, and 2016, respectively. From 2017 to 2019, he was a Postdoctoral Researcher at RUDN University. He took part in the Erasmus Student Program at the Faculty of Electrical Engineering, University of Ljubljana, in 2012 and 2013, and a Visitor Researcher at Tampere University, Finland, in 2014. He is a Research Associate Professor with the Centre for Telecommunication, Sri Lanka Technological Campus, Padukka, Sri Lanka. He has been an Active Member of the Technical Program Committee on many international conferences and journals. He is the Expert at the Judges Panel and the Challenge Management Board at AI-5G-Challenge, ITU, and a Russian Host Organizer. His research interests include wireless communications, 5G/6G cellular systems, the IoT applications, edge computing, and software-defined networking.