Opportunistic Non-Orthogonal Random Access With Optimal Decoder for 6G Multi-Channel IoT Networks

Jeong Seon Yeom, *Member, IEEE*, and Bang Chul Jung, *Senior Member, IEEE*

***Abstract*—A novel opportunistic non-orthogonal random access (O-NORA) technique is proposed for multi-channel systems in sixth-generation (6G) massive connection scenarios, such as Internet of Things (IoT) networks. In this letter, *K* IoT devices (IDs) independently transmit their packets to a single access point (AP) over one of *M* available channels. To meet the low-complexity requirements of IoT applications, all nodes are assumed to operate with a single antenna. Specifically, the optimal simultaneous non-unique decoding (SND) technique is leveraged at the AP to enhance network reliability. A rigorous mathematical analysis of the outage probability and channel utilization for the proposed O-NORA technique is provided. The accuracy of our analytical results is validated through simulations. The proposed O-NORA with SND demonstrates a significant performance gain over conventional schemes in terms of outage probability and throughput for 6G multi-channel uplink IoT networks.**

***Index Terms*—6G mobile communications, massive IoT networks, non-orthogonal random access, opportunistic transmission, outage probability, simultaneous non-unique decoding.**

I. Introduction

AMONG the various applications of massive communication, Internet of Things (IoT) networks stand out as a key enabler for achieving 6G's massive connectivity goals, connecting billions of devices across diverse domains [1]. In IoT networks, an access point (AP) suffers from accommodating many diverse communicating devices since IoT devices (IDs) have unique characteristics with sporadic traffic patterns in general [2]. New wireless transmission technologies are increasingly required to meet the demands of industrial and large-scale IoT systems [3]. Non-orthogonal random access (NORA) has recently been proposed as an emerging technology to satisfy such harsh performance requirements, including low latency, high reliability, and low power consumption [4], [5]. While NOMA also processes a fixed number of superimposed signals, NORA is based on random access, and therefore, the number of received signals is not fixed. As a result, NORA is more suitable for IoT networks than NOMA, as it allows devices to transmit only when necessary, reducing channel resource waste and improving scalability in massive connection scenarios. Not only in IoT networks but also in another large-scale network, the cell-free massive MIMO system, an outage probability analysis was conducted by adopting grant free-NOMA (GF-NOMA) similar to NORA [6].

Performance analysis of the NORA technique has been actively conducted for single or multiple channels, assuming various encoding and decoding schemes. The traditional interference as noise (IAN) decoding and successive interference cancellation (SIC) decoding schemes have been widely used in the literatures [7], [8], [9]. In [7], [8], the authors showed that the maximum channel gain selection yields significant performance improvement in throughput and energy efficiency for multi-channel NORA systems with SIC receivers. In addition, a truncated channel inversion with opportunistic transmission was considered to enhance energy efficiency further [8]. In [9], the NORA with space-time line code was proposed for multi-channel uplink networks and was mathematically analyzed in terms of the throughput, distribution of received signal-to-noise ratio (SNR), and energy efficiency. It is worth noting that all studies mentioned above assume that the receiver exploits SIC-based decoding techniques. However, significant performance degradation of the SIC may occur due to error propagation, and the lack of power control in NORA makes it difficult to maintain proper SNR ordering among users. This leads to performance saturation even at high SNRs.

Instead of SIC, joint decoding (JD) scheme has also been considered for several uplink NOMA and NORA systems [10], [11]. The JD scheme decodes all signals simultaneously without treating other signals as interference, and thus there is no error propagation phenomenon. Although JD's performance significantly surpasses SIC's, JD is also not the optimal decoding scheme in uplink NORA systems. The simultaneous non-unique decoding (SND) scheme was initially proposed as the *optimal* decoding technique for the general multi-transmitter and multi-receiver interference channel [12]. Briefly, SND enables receivers to decode both desired and interfering messages. It achieves the optimal rate region $\mathcal{R}$ by unifying IAN decoding and JD schemes. Thus, $\mathcal{R}$ is given as $\mathcal{R}_{\text{IAN}} \cup \mathcal{R}_{\text{JD}}$, where $\mathcal{R}_{\text{IAN}}$ and $\mathcal{R}_{\text{JD}}$ represent the respective rate regions. However, existing outage probability analyses of SND have been limited to the case where only two signals are simultaneously received [13].

In this letter, a novel opportunistic NORA (O-NORA) technique is proposed, which exploits the optimal SND as the decoding scheme in multi-channel uplink IoT networks.

Received 8 April 2025; revised 30 April 2025; accepted 9 May 2025. Date of publication 15 May 2025; date of current version 11 July 2025. This work was supported in part by the Institute for Information and Communications Technology Promotion (IITP) Grant funded by the Korea Government (MSIT), Development of Cube Satellites Based on Core Technologies in Low Earth Orbit Satellite Communications under Grant RS-2024-00396992, and in part by the MSIT, South Korea, under the Information Technology Research Center (ITRC) Support Program supervised by the IITP under Grant IITP-2024-RS-2024-00436406. The associate editor coordinating the review of this article and approving it for publication was X. Li. *(Corresponding author: Bang Chul Jung.)*

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Digital Object Identifier 10.1109/LWC.2025.3569601

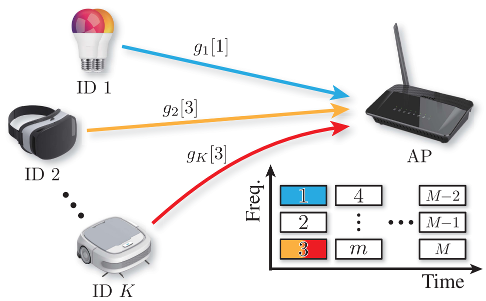

Fig. 1. System model of non-orthogonal random access with multiple channels in uplink 6G IoT networks.

Unlike non-opportunistic NORA, if its channel gain is larger than a certain threshold, one channel is independently selected for packet transmission at each ID. By leveraging this threshold-based selection, O-NORA further enhances energy efficiency by preventing unnecessary transmissions over poor channel conditions, thereby reducing power consumption and improving network longevity. To the best of our knowledge, this is the first study that considers the optimal SND scheme at the receiver in uplink NORA systems. The proposed technique performs better than the SIC in terms of the outage probability. We mathematically analyze the outage probability of the proposed technique by considering a single-slot performance analysis in a slotted-ALOHA environment, regardless of the number of IDs in the network.

Notation: $\mathcal{S}_{\mathsf{sub}} \subseteq_{\{x\}} \mathcal{S}$ for given set $\mathcal{S}$ containing an element x is defined as the subset, which includes a certain element x, of the set $\mathcal{S}$.

II. System Model

As illustrated in Fig. 1, the uplink IoT network consists of one AP and K IDs, each equipped with a single antenna. Each k-th ID generates a signal with a probability of $p_{\mathrm{g},k}$ and employs a single-signal buffer to store the generated signal. In this network, each ID is allowed to transmit packets through one of the M channels, and it is assumed that $K \geq M$, considering the practical conditions of massive IoT networks. Data transmission to the AP is allowed only for IDs having one or more channel gain values among M channels greater than a certain threshold. Let us define the set of eligible channels for the k-th ($k \in \{1, 2, \ldots, K\}$) ID as

$$\mathcal{M}_k = \left\{ m \mid \Lambda_k^{-1} |h_k[m]|^2 > \tau_k, m \in \{1, 2, \ldots, M\} \right\}, \quad (1)$$

where Λ_k denotes the constant-valued large-scale fading loss from the k-th ID to AP and $h_k[m]$ denotes small-scale fading channel coefficient from the k-th ID to AP through the m-th channel ($m \in \{1, 2, \ldots, M\}$). In addition, τ_k represents the channel gain threshold of the k-th ID for data transmission.[1] For convenience and without loss of generality, it is assumed that all of the small-scale fading channel coefficients follow identically and independently distributed (i.i.d.) complex Gaussian distribution with zero mean and unit variance for all k and m, i.e., $h_k[m] \sim \mathcal{CN}(0, 1)$ $(\forall k, \forall m)$. If the set of eligible channels $\mathcal{M}_k$ is non-empty, the k-th ($\forall k$) ID randomly selects one channel index from $\mathcal{M}_k$ with equal probability, i.e., according to a discrete uniform distribution over $\mathcal{M}_k$, and transmits its packet over the selected channel. Consequently, multiple IDs may independently select the same channel, resulting in simultaneous transmissions. If a signal is ready for transmission but the channel condition does not satisfy the required threshold, the signal remains in the buffer without being transmitted. Let us define another set of indices of IDs transmitting packets through the m-th channel as $\mathcal{D}[m]$. Then, the received signal at the AP is given by

$$y[m] = \sum_{u \in \mathcal{D}[m]} g_u[m] x_u + n[m], \quad (2)$$

where $y[m]$ ($m \in \{1, 2, \ldots M\}$) denotes the received signal of AP at the m-th channel. The AP is assumed to identify IDs in $D[m]$ by attaching an exclusive preamble in the packet at each ID. The term $g_u[m] \triangleq \sqrt{P_u \Lambda_u^{-1}} h_u[m]$ ($m \in \mathcal{M}_k$) represents the product of the square root of the transmission power P_u at the u-th ID and the effective channel coefficient of the m-th channel selected by the u-th ID for packet transmission. The effective channel coefficient includes the constant-valued large-scale fading loss Λ_u and small-scale fading channel $h_u[m]$. It is worth noting that due to transmitter-specific parameters, the channel-related term $g_u[m]$ can be independent but not necessarily identically distributed across different transmitters. The signal of the u-th ID is represented as x_u with unit power, i.e., $\mathbb{E}[|x_u|^2] = 1$, and the additive white Gaussian noise at the AP via the m-th channel is represented as $n[m] \sim \mathcal{CN}(0, N_p)$.

The AP tries to decode the signal of IDs in $\mathcal{D}[m]$ by the SND technique for all channels. The AP is assumed to know the channel state information (CSI) for all IDs through exclusive preamble insertion and detection procedure. With the network information theory perspective [12], individual successful decoding conditions of the SND technique for the k-th ID in the m-th channel are given by

$$\mathscr{S}_k[m] = \left\{ \begin{array}{l} \left\{ \bigcap\limits_{\forall \mathcal{K} \subseteq_{\{k\}} \mathcal{D}[m]} \log_2\left(1 + \sum\limits_{u \in \mathcal{K}} \frac{|g_u[m]|^2}{N_p}\right) \geq \sum\limits_{u \in \mathcal{K}} R_u \right\} \\ \bigcup \log_2\left(1 + \frac{|g_k[m]|^2}{\sum\limits_{v \in \mathcal{D}[m] \setminus \{k\}} |g_v[m]|^2 + N_p}\right) \geq R_k \end{array} \right\} \quad (3)$$

where R_k denotes the target rate of the k-th ID, respectively.

III. Performance Analysis

In this section, the outage probability of the proposed O-NORA is mathematically analyzed in uplink IoT networks. Without loss of generality, it is assumed that the k-th ID transmits the signal through the m-th ($m \in \mathcal{M}_k$) channel. With the total probability theorem, the outage probability of the k-th ID of the proposed O-NORA technique is given by[2]

$$P_{o,k} = \sum_{\forall \mathcal{D} \subseteq_{\{k\}} \{1,2,\ldots,K\}} P_{o,k|\mathcal{D}} \times \Pr\{\mathcal{D} | \mathcal{D} \in k\}, \quad (4)$$

where $P_{o,k|\mathcal{D}}$ denotes the conditional outage probability of the k-th ID for given the set $\mathcal{D}$ including the element k. Note that all possible $\mathcal{D}$ are mutually exclusive since all IDs

[1]The threshold τ_k plays a key role in determining the opportunistic gain; increasing τ_k reduces the error probability but decreases the amount of transmitted data due to fewer transmission opportunities.

[2]For notational simplicity, the $[m]$ index is omitted hereafter.

have a binary state for each channel, and the indices of IDs not included in $\mathcal{D}$ imply that they are not transmitting on that channel. Thus, different $\mathcal{D}$ cannot coincide. Based on the successful decoding conditions (3), the exact conditional outage probability is given as follows:

$$P_{o,k|\mathcal{D}} = \Pr\left\{ \begin{array}{l} \left\{ \bigcup\limits_{\forall \mathcal{K} \subseteq_{\{k\}} \mathcal{D}} \log_2\left(1 + \sum\limits_{u\in\mathcal{K}} \frac{|g_u|^2}{N_p}\right) < \sum\limits_{u\in\mathcal{K}} R_u \right\} \\ \bigcap \log_2\left(1 + \frac{|g_k|^2}{\sum\limits_{v\in\mathcal{D}\setminus\{k\}} |g_v|^2 + N_p}\right) < R_k \end{array} \right\}. \quad (5)$$

It is worth noting that the independent outage events of the proposed O-NORA technique are not mutually exclusive, i.e., the entire outage event consists of non-partitioned outage events. This makes it difficult to mathematically derive an exact outage probability. Hence, a lower bound of the conditional outage probability for the proposed O-NORA technique is derived as follows:

$$\begin{aligned} P_{o,k|\mathcal{D}} &\geq \Pr\left\{ \begin{array}{l} \log_2\left(1 + \sum\limits_{u\in\mathcal{D}} \frac{|g_u|^2}{N_p}\right) < \sum\limits_{u\in\mathcal{D}} R_u \\ \bigcap \log_2\left(1 + \frac{|g_k|^2}{\sum\limits_{v\in\mathcal{D}\setminus\{k\}} |g_v|^2 + N_p}\right) < R_k \end{array} \right\} \\ &= \underbrace{\Pr\left\{ \sum_{u\in\mathcal{D}} |g_u|^2 < \left(2^{R_{\mathcal{D}}} - 1\right) N_p \right\}}_{\triangleq P^1_{o,k|\mathcal{D}}} \\ &\quad \times \underbrace{\Pr\left\{ \frac{|g_k|^2}{2^{R_k} - 1} - N_p < \sum_{v\in\mathcal{D}\setminus\{k\}} |g_v|^2 \right\}}_{\triangleq P^2_{o,k|\mathcal{D}}}, \end{aligned} \quad (6)$$

where $R_{\mathcal{D}} \triangleq \sum_{u\in\mathcal{D}} R_u$.

Since the opportunistic transmission based on the channel gain is employed as in (1), the channel gain selected by the k-th ID is greater than the threshold τ_k. Thus, $|g_k[m]|^2$ $(m \in \mathcal{M}_k)$ follows a truncated exponential distribution with parameter of $P_k\tau_k$. Let $\lambda_k \triangleq \Lambda_k P_k^{-1}$. Then, the probability density function of $|g_k[m]|^2$ $(m \in \mathcal{M}_k)$ is given by

$$f_{|g_k|^2}(x) = \frac{\lambda_k \exp(-\lambda_k x)}{\exp(-\lambda_k P_k \tau_k)}, \quad x \in (P_k\tau_k, \infty]. \quad (7)$$

In order to solve (6), it is necessary to characterize the distribution of the sum of truncated exponential random variables (RVs). If all λ_k are different, $|g_{\mathcal{D}}|^2 \triangleq \sum_{k\in\mathcal{D}} |g_k|^2$ follows a *shifted hypoexponential* distribution:

$$f_{|g_{\mathcal{D}}|^2}(z) = \sum_{u\in\mathcal{D}} \left(\prod_{v\in\mathcal{D}\setminus\{u\}} \frac{\lambda_v}{\lambda_v - \lambda_u} \right) \lambda_u \exp\left(-\lambda_u\left(z - \tau_{\mathcal{D}}\right)\right), \quad \text{for } z \in (\tau_{\mathcal{D}}, \infty] \quad , \tau_{\mathcal{D}} \triangleq \sum_{u\in\mathcal{D}} P_k\tau_k. \quad (8)$$

Proof: Refer to Appendix . ■

Then, $P^1_{o,k|\mathcal{D}}$ in (6) is obtained through cumulative density functions of (7) and (8) according to the cardinality of the set $\mathcal{D}$ as follows:

$$P^1_{o,k|\mathcal{D}} = \begin{cases} 1 - \exp\left(-\lambda_{\mathcal{D}}\left\{\left(2^{R_{\mathcal{D}}} - 1\right)N_p - \tau_{\mathcal{D}}\right\}\right), & \text{for } |\mathcal{D}| = 1 \\ \sum\limits_{k\in\mathcal{D}} \left(\prod\limits_{u\in\mathcal{D}\setminus\{k\}} \frac{\lambda_u}{\lambda_u - \lambda_k} \right) \left[1 - \exp\left(-\lambda_k\left\{\frac{2^{R_{\mathcal{D}}} - 1}{N_p^{-1}} - \tau_{\mathcal{D}}\right\}\right)\right], & \text{for } |\mathcal{D}| \geq 2. \end{cases} \quad (9)$$

Similarly, $P^2_{o,k|\mathcal{D}}$ in (6) is derived according to the relationship between the threshold values of two random variables following different truncated distributions.

$$P^2_{o,k|\mathcal{D}} = \Pr\left\{ \frac{|g_k|^2}{2^{R_k} - 1} - N_p < |g_{\mathcal{D}\setminus\{k\}}|^2 \right\} \quad (10)$$
$$= \begin{cases} \int_{P_k\tau_k}^{\infty} \int_{\max\left(\tau_{\mathcal{D}\setminus\{k\}}, \frac{x}{2^{R_k}-1} - N_p\right)}^{\infty} f_{|g_k|^2}(x) f_{|g_{\mathcal{D}\setminus\{k\}}|^2}(z)\, dz dx, & \text{for } \frac{P_k\tau_k}{2^{R_k}-1} - N_p < \tau_{\mathcal{D}\setminus\{k\}} \\ \int_{P_k\tau_k}^{\infty} \int_{\frac{x}{2^{R_k}-1} - N_p}^{\infty} f_{|g_k|^2}(x) f_{|g_{\mathcal{D}\setminus\{k\}}|^2}(z)\, dz dx, & \text{for } \frac{P_k\tau_k}{2^{R_k}-1} - N_p \geq \tau_{\mathcal{D}\setminus\{k\}}. \end{cases}$$

The probability $P^2_{o,k|\mathcal{D}}$ is further derived as (11), shown at the bottom of the next page, for $P_k\tau_k/(2^{R_k} - 1) - N_p < \tau_{\mathcal{D}\setminus\{k\}}$ and (12), shown at the bottom of the next page, for $P_k\tau_k/(2^{R_k} - 1) - N_p \geq \tau_{\mathcal{D}\setminus\{k\}}$ in the next page, respectively, where $\eta_{\mathcal{D}\setminus\{k\}} \triangleq (\tau_{\mathcal{D}\setminus\{k\}} + N_p)(2^{R_k} - 1)$. In particular, (12) is derived from a part of the derivation process of (11). Consequently, the lower bound of the conditional outage probability for the proposed O-NORA technique with the SND scheme is obtained by substituting (9) and (11) or (12) into (6), considering the relationship between the threshold values of the channel gains.

Now, the probability of a successful decoding set, $\Pr \mathcal{D}|\mathcal{D} \in k$ in (4), is derived from the transmission probability of the IDs. If at least one channel has a greater gain than the threshold in each ID, then the ID sends a packet to the AP via the channel. Firstly, the probability that the channel condition for transmission is satisfied at the k-th ID, $p_{\mathsf{c},k}$, can be easily obtained from its non-transmission probability, q_k, as follows:

$$\begin{aligned} p_{\mathsf{c},k} &= 1 - q_k = 1 - \left\{ \int_0^{P_k\tau_k} f_{\lambda_k^{-1}|h_k|^2}(x)\, dx \right\}^M \\ &= 1 - \{\textstyle\int_0^{P_k\tau_k} \lambda_k \exp(-\lambda_k x)\, dx\}^M = 1 - \{1 - \exp(-\lambda_k P_k\tau_k)\}^M. \end{aligned} \quad (13)$$

A packet is successfully transmitted only when it either arrives at the current time slot or remains buffered from a previous slot, and the instantaneous channel condition meets the transmission criterion with probability p_t. In other words, a discrete-time queueing system with stochastic arrivals and opportunistic transmissions is considered, where a packet is transmitted only when the transmission condition is satisfied. Consequently, the system is modeled as a Geo/Geo/1 queue, incorporating probabilistic packet arrivals and channel-aware transmission opportunities.

Let π_0 and π_1 denote the steady-state probabilities that the buffer is empty and non-empty, respectively. The system can be represented as a two-state Markov chain, where the states correspond to the absence or presence of a packet in the buffer. The state transition probabilities depend on the packet arrival probability $p_{\mathsf{g},k}$ and the transmission success probability $p_{\mathsf{g},k}$. The transition probability matrix for the k-th ID is given by:

$$\mathbf{P} = \begin{bmatrix} 1 - p_{\mathsf{g},k} & p_{\mathsf{g},k} \\ p_{\mathsf{c},k}(1 - p_{\mathsf{g},k}) & 1 - p_{\mathsf{c},k}(1 - p_{\mathsf{g},k}) \end{bmatrix}. \quad (14)$$

The steady-state distribution $[\pi_0 \quad \pi_1]^T$ satisfies the balance equation $[\pi_0 \quad \pi_1]^T = \mathbf{P}[\pi_0 \quad \pi_1]^T$, along with the normalization condition $\pi_0 + \pi_1 = 1$. Solving the balance equations yields the steady-state probability $\pi_1 = p_{\mathsf{g},k}/(p_{\mathsf{c},k} + p_{\mathsf{g},k} - p_{\mathsf{c},k}p_{\mathsf{g},k})$.

TABLE I
TOTAL DECODING COMPLEXITY OF AP FOR K IDS AT SINGLE CHANNEL

IAN	JD	SND
$\sum_{k=1}^{K} \mathcal{O}(2^{nR_k})$	$\mathcal{O}\left(2^{n\sum_{k=1}^{K} R_k}\right)$	$\mathcal{O}\left(2^{n\sum_{k=1}^{K} R_k}\right)$

Hence, the actual transmission probability of k-th ID at any time slot is expressed as:

$$p_{\mathsf{t},k} = p_{\mathsf{c},k}\pi_1 = \frac{p_{\mathsf{c},k}p_{\mathsf{g},k}}{p_{\mathsf{c},k} + p_{\mathsf{g},k} - p_{\mathsf{c},k}p_{\mathsf{g},k}}. \tag{15}$$

As a results, the probability that a certain channel of the k-th ID among M channels belongs to a set $\mathcal{D}$ is given by

$$\Pr\{\mathcal{D}|\mathcal{D}\in k\} = \left\{\prod_{u\in\mathcal{D}} p_u \prod_{v\in\mathcal{D}^c}(1-p_v)\right\}\left(\frac{p_{\mathsf{t},k}}{M}\right)^{-1}. \tag{16}$$

Finally, substituting (6) and (16) into (4), the lower bound of the outage probability for the proposed O-NORA with the SND scheme is obtained as follows:

$$P_{o,k} \geq \sum_{\substack{\forall\mathcal{D}\subseteq_{\{k\}}\\ \{1,2,\ldots,K\}}} \frac{M}{p_{\mathsf{t},k}}\left\{\prod_{u\in\mathcal{D}} p_u \prod_{v\in\mathcal{D}^c}(1-p_v)\right\}\left(P^1_{o,k|\mathcal{D}} \times P^2_{o,k|\mathcal{D}}\right). \tag{17}$$

Furthermore, the average channel utilization U_{ch}, representing the expected number of channels used per time slot, can be easily obtained from (15) as follows:

$$U_{\text{ch}} = M\left\{1 - \prod_{k=1}^{K}\left(1 - \frac{p_{t,k}}{M}\right)\right\}. \tag{18}$$

The decoding complexity according to the decoding technique is shown in Table I. The big-$\mathcal{O}$ complexities for the codeword length n at the AP are analyzed when K IDs are transmitted on one channel. To mitigate the decoding complexity of SND, a hybrid decoding strategy that first applies SIC to strong signals and subsequently performs SND on the remaining signals could be considered, even at the cost of tolerating a small amount of residual errors.

IV. NUMERICAL RESULTS

In this section, the performance of the proposed O-NORA technique with the SND scheme is evaluated in uplink multi-subcarrier IoT networks. The accuracy of the analytical results is validated by comparing them with Monte Carlo simulation results. For the computer simulations in this section, the parameters are set as follows: bandwidth $BW = 15$ kHz, noise spectral density $N_0 = -174$ dBm/Hz, noise figure $NF = 5$ dB, i.e., noise power $N_p = 10\log(BW) + (N_0 - 30) + NF = -119$ dB, and the constant-valued large scale fading loss $\Lambda_k = d_k^3 \cdot SW$ where d_k (meter) denotes the distance between the k-th ID and the AP and SW represents the shadowing and penetration losses, which is given as 30 dB. This IoT network consists of 10 IDs ($K = 10$) and three channels ($M = 3$). The distances between IDs and the AP are set as $(30, 30, 35, 35, 40, 40, 45, 45, 50, 50)$ meters.

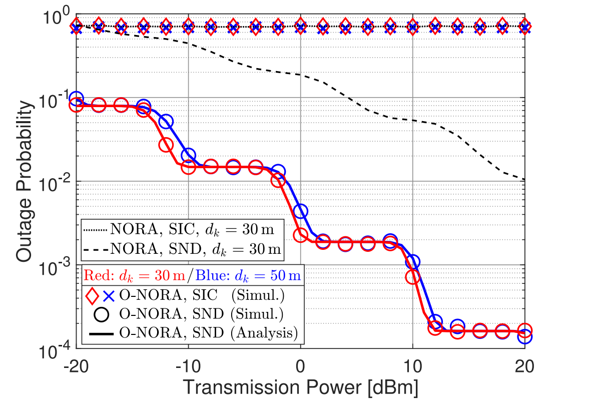

Fig. 2. Outage probability of the NORA and proposed O-NORA techniques with SND and SIC for multi-subcarreir uplink IoT networks.

Fig. 2 shows the outage probability of the O-NORA technique with IAN decoding, JD, and SND for varying SNR values when $R_k = 4$ bits/s/Hz for all k, the transmission probability $p_{\mathsf{c},k} = 0.4$, and $p_{\mathsf{g},k} = 0.75$, i.e., $p_{\mathsf{t},k} \approx 0.353$. For given transmission probability, with (13), the channel threshold is given by $\tau_k = -\ln(1-(1-p_{\mathsf{c},k})^{1/M})/\lambda_k$. And, the analytical channel utilization is $U_{\text{ch}} = 2.1419$, while the simulation result is 2.1448, showing a very close match and validating the analysis. Fig. 2 shows that our analytical lower bound on the outage probability of the proposed O-NORA technique with the SND scheme is very tight to the actual outage probability obtained by extensive computer simulations for all transmission power region. The SIC based NORA becomes ineffective at practical transmit power levels, and the non-opportunistic NORA, labeled as 'NORA', exhibits significantly higher outage probability than O-NORA due to its lower average channel gain.

Fig. 3 shows the outage probability (grayscale) and effective throughput (colored curves) of the O-NORA technique with

$$\begin{aligned} P^2_{o,k|\mathcal{D}} &= \int_{P_k\tau_k}^{\infty}\int_{\max\left(\tau_{\mathcal{D}\setminus\{k\}},\frac{x}{2^{R_k}-1}-N_p\right)}^{\infty} \frac{\lambda_k\exp(-\lambda_k x)}{\exp(-\lambda_k P_k\tau_k)}\left\{\sum_{u\in\mathcal{D}\setminus\{k\}}\left(\prod_{v\in\mathcal{D}\setminus\{k,u\}}\frac{\lambda_v}{\lambda_v-\lambda_u}\right)\lambda_u\exp\left\{-\lambda_u\left(z-\tau_{\mathcal{D}\setminus\{k\}}\right)\right\}\right\}dzdx \\ &= \sum_{u\in\mathcal{D}\setminus\{k\}}\left(\prod_{v\in\mathcal{D}\setminus\{k,u\}}\frac{\lambda_v}{\lambda_v-\lambda_u}\right)\left[1-\frac{\lambda_u/(2^{R_k}-1)}{\lambda_k+\lambda_u/(2^{R_k}-1)}\exp\left\{\lambda_k\left(P_k\tau_k-\eta_{\mathcal{D}\setminus\{k\}}\right)\right\}\right]. \end{aligned} \tag{11}$$

$$P^2_{o,k|\mathcal{D}} = \sum_{u\in\mathcal{D}\setminus\{k\}}\left(\prod_{v\in\mathcal{D}\setminus\{k,u\}}\frac{\lambda_v}{\lambda_v-\lambda_u}\right)\left[\frac{\lambda_k}{\lambda_k+\lambda_u/(2^{R_k}-1)}\exp\left\{-\frac{\lambda_u\eta_{\mathcal{D}\setminus\{k\}}-\lambda_u P_k\tau_k}{2^{R_k}-1}\right\}\right]. \tag{12}$$

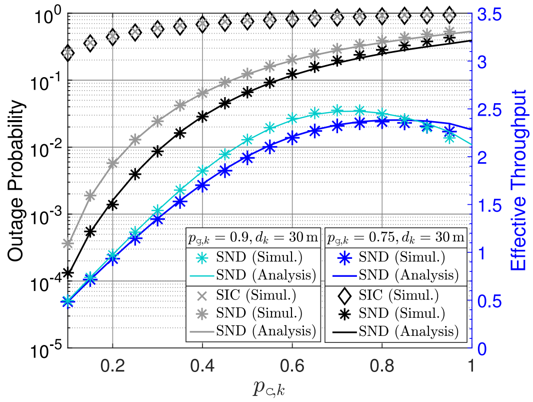

Fig. 3. Outage probability and effective throughput of the O-NORA technique with SND ans SIC for multi-subcarreir uplink IoT networks.

SND and SIC for varying $P_{c,k}$ when $P_k = 1$ mW, $R_k = 5$ bits/s/Hz for all k, and $p_{g,k} = 0.75$ and 0.9. The effective throughput is defined as $T_k \triangleq R_k{\cdot}p_{c,k}(1-P_{o,k})$ and the upper bound of the effective throughput can be obtained by using the analyzed lower bound of the outage probability in (17). The outage probability decreases as the transmission probability decreases since a lower transmission probability with a higher channel threshold guarantees a higher received SNR in O-NORA. On the other hand, as the transmission probability increases, the effective throughput initially rises but begins to decline beyond a certain point. For example, the maximum throughput is achieved when $p_{c,k} = 0.82$ if $p_{g,k} = 0.75$, while the throughput is maximized when $p_{c,k} = 0.73$ if $p_{g,k} = 0.9$. Hence, the transmission probability must be carefully adjusted according to system parameters in the proposed O-NORA technique with the SND scheme. In terms of analytical accuracy, the error tends to increase as $p_{c,k}$ increases. This is because our analysis ignores a larger number of outage-causing events as the number of simultaneously transmitting IDs increases.

V. Conclusion

In this letter, a novel opportunistic non-orthogonal random access (O-NORA) technique employing the optimal simultaneous non-unique decoding (SND) scheme at the receiver was proposed for 6G multi-channel uplink IoT networks. Each IoT device (ID) independently transmits a packet over one of multiple channels, provided that at least one channel exceeds a predefined gain threshold. A mathematical analysis of the outage probability was conducted, and its accuracy was validated through computer simulations. Our results demonstrated that the proposed O-NORA technique significantly outperforms conventional approaches in terms of outage probability and throughput. Nonetheless, the SND method is more complex than the interference as noise (IAN) decoding and joint decoding (JD) due to its synthetic decoding structure, so care must be taken when designing actual systems. The analytical results derived in this letter can also serve as useful tools for guiding practical optimization of system parameters in dynamic random access networks.

Appendix

The characteristic function of truncated exponential RV is

$$\Phi_{|g_k|^2}(t) = \int_{P_k\tau_k}^{\infty} e^{itx}\frac{\lambda_k \exp(-\lambda_k x)}{\exp(-\lambda_k P_k \tau_k)}\,dx = \frac{\lambda_k}{\lambda_k - it}\exp(itP_k\tau_k).$$

The characteristic function of the sum of independent RVs is equal to the product of characteristic functions of the independent RVs. Then,

$$\Phi_{|g_{\mathcal{D}}|^2}(t) = \prod\nolimits_{u\in\mathcal{D}}\Phi_{|g_u|^2}(t) = e^{it\tau_{\mathcal{D}}}\prod\nolimits_{u\in\mathcal{D}}\frac{\lambda_u}{\lambda_u - it}. \quad (19)$$

By Heaviside cover-up method for partial fraction, the product term in (19) is given as follows:

$$\prod\nolimits_{u\in\mathcal{D}}\frac{\lambda_u}{\lambda_u - it} = \sum\nolimits_{u\in\mathcal{D}}\left(\prod\nolimits_{v\in\mathcal{D}\setminus\{u\}}\frac{\lambda_v}{\lambda_v-\lambda_u}\right)\frac{\lambda_u}{\lambda_u - it}.$$

Therefore, the p.d.f. of RV $|g_{\mathcal{D}}|^2$ is derived as follows:

$$f_{|g_{\mathcal{D}}|^2}(z) = \frac{1}{2\pi}\int_{-\infty}^{\infty} e^{-itz}\Phi_{|g_{\mathcal{D}}|^2}(t)\,dt$$
$$= \sum_{u\in\mathcal{D}}\left(\prod_{v\in\mathcal{D}\setminus\{u\}}\frac{\lambda_u}{\lambda_u-\lambda_v}\right)\lambda_u e^{-\lambda_u(z-\tau_{\mathcal{D}})},\ \text{for } z\in(\tau_{\mathcal{D}},\infty]. \quad (20)$$

If $\tau_{\mathcal{D}} = 0$ in (20), it is known as the hypoexponential distribution and then if $\tau_{\mathcal{D}} > 0$, it is the shifted hypoexponential distribution by $\tau_{\mathcal{D}}$.

References

[1] L. Mohjazi et al., "The journey toward 6G: A digital and societal revolution in the making," *IEEE Internet Things Mag.*, vol. 7, no. 2, pp. 119–128, Mar. 2024.

[2] Z. Gao et al., "Compressive-sensing-based grant-free massive access for 6G massive communication," *IEEE Internet Things J.*, vol. 11, no. 5, pp. 7411–7435, Mar. 2024.

[3] H. Wang et al., "Low-complexity MIMO-FBMC sparse channel parameter estimation for industrial big data communications," *IEEE Trans. Ind. Informat.*, vol. 17, no. 5, pp. 3422–3430, May 2021.

[4] Y. Liu et al., "Evolution of NOMA toward next generation multiple access (NGMA) for 6G," *IEEE J. Sel. Areas Commun.*, vol. 40, no. 4, pp. 1037–1071, Apr. 2022.

[5] E. A. Jorswieck, "Next-generation multiple access: From basic principles to modern architectures," *Proc. IEEE*, vol. 112, no. 9, pp. 1149–1178, Sep. 2024.

[6] J. Li, C. Zhang et al., "HARQ-assisted grant-free access scheme in cell-free massive MIMO system," *IEEE Internet Things J.*, vol. 12, no. 1, pp. 739–749, Jan. 2025.

[7] J. Choi, "NOMA-based random access with multichannel ALOHA," *IEEE J. Sel. Areas Commun.*, vol. 35, no. 12, pp. 2736–2743, Dec. 2017.

[8] J.-B. Seo et al., "Multichannel uplink NOMA random access: Selection diversity and bistability," *IEEE Commun. Lett.*, vol. 23, no. 9, pp. 1515–1519, Sep. 2019.

[9] J.-B. Seo et al., "Uplink NOMA random access systems with space–time line code," *IEEE Trans. Veh. Technol.*, vol. 69, no. 4, pp. 4522–4526, Apr. 2020.

[10] J. S. Yeom et al., "Spectrally efficient uplink cooperative NOMA with joint decoding for relay-assisted IoT networks," *IEEE Internet Things J.*, vol. 10, no. 1, pp. 210–223, Jan. 2023.

[11] S. A. Tegos et al., "Slotted ALOHA with NOMA for the next generation IoT," *IEEE Trans. Commun.*, vol. 68, no. 10, pp. 6289–6301, Oct. 2020.

[12] B. Bandemer et al., "Optimal achievable rates for interference networks with random codes," *IEEE Trans. Inf. Theory*, vol. 61, no. 12, pp. 6536–6549, Dec. 2015.

[13] F. R. Ghadi et al., "Fluid antenna multiple access with simultaneous non-unique decoding in strong interference channel," Oct. 2024, *arXiv:2410.20930*.