Decentralized Power Control for Short Packet Transmission with Multi-Packet Reception

Ni Tian[1], Shibo Sun[1], Long Zhang[1,2], Boao Dong[1], Deshi Ding[1], Shangze Lu[1]

{tianni@hebeu.edu.cn[1], ssbddzyx7@gmail.com[1], zhanglong@hebeu.edu.cn[1,2],}

{b.dong1217@gmail.com[1], dds20000109@gmail.com[1], lusz102816@gmail.com[1]}

Hebei University of Engineering, Taiji Road 19, 056038 Handan, China[1]

Chongqing University of Posts and Telecommunications, Chongwen Road 2, 400065 Chongqing, China[2]

Abstract. The growth of IoT demands efficient massive machine-type communication with short packet transmission. To address packet collisions in grant-free access, this paper proposes a multi-level decentralized power control (MLP-based) scheme for short packets. The scheme decouples the number of power levels from active devices, enabling effective multi-packet reception via SIC. Further, the paper derives a closed-form lower bound for the packet reception probability and analyzes the impact of key parameters. Numerical results show that the proposed scheme significantly outperforms the existing NOMA-based scheme.

Keywords: short packet transmission, multi-level decentralized power control, collided packets reception probability.

1 Introduction

The meteoric rise of the Internet of Things (IoT) is driving the demand for massive machine-type communication (mMTC), which is characterized by a massive number of devices transmitting short data packets in a sporadic and uncoordinated manner [1]. Owing to its capability to integrate channel requests with data transmission, grant-free random access (RA) effectively mitigates signaling overhead and is thus considered a promising candidate for massive mMTC transmitting short packets [2]. However, the massive devices access poses a significant challenge for grant-free random access, which is that collisions caused by simultaneous transmission will bring packet loss and degrade system performance. How to guarantee the reception probability of collided packets is critical for future massive machine-type communication.

To overcome the collision problem, Multi-Packet Reception (MPR) techniques, which enable the receiver to decode multiple superposed packets, have been extensively studied. Successive Interference Cancellation (SIC) has been proven to be a potent solution for MPR [3], the core of which lies in artificially created power differences for devices or users to progressively separate the non-orthogonally superimposed mixed signal. Thus, it is essential to assign distinct levels of transmission

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powers to different users, e.g., non-orthogonal multiple access (NOMA) allocating higher power to users with poor channel conditions, for SIC. The early work [4] proposed the decentralized power control with SIC for random access, for which each device randomly selects its transmission power level according to a power distribution, and demonstrated the optimal power distributions are of discrete nature. Based on this basic work, [5] explored decentralized power allocation algorithms for the uplink random access in the CR network with SIC and proposed a novel algorithm to optimize the corresponding probabilities, which can improve system performance.

Furthermore, the decentralized power control is combined with NOMA to be applied for random multiple access protocols, such as NOMA-ALOHA [6][7], NOMA-IRSA [8][9]. [6] analyzed the throughput of NOMA-ALOHA uplink transmissions for massive IoT with the number of active users in each power level follows the binomial distribution and power levels. [7] gave the upper and lower bounds of the maximum throughput of NOMA-ALOHA with different power levels. [8] proposed the IRSA-NOMA system, which operates in a time-slotted manner with finite frame length, leveraging NOMA with two power levels and an adaptive transmission strategy. [9] explored the NOMA-IRSA system performance with the power levels being coupled with the active devices. The literature studied different decentralized power control schemes to improve collided packets reception for random access protocols and gave the numerical analysis for the system performance.

However, the literature primarily focuses on infinite blocklength transmission, where the packet error probability is negligible. This assumption is invalid for machine-type communication scenarios, such as industrial automation and vehicular networks, which involve short packet transmissions. In the finite blocklength regime, the packet decoding error probability becomes non-negligible and is heavily influenced by the coding rate, packet length, and signal-to-interference-plus-noise ratio (SINR) [10]. Besides, the existing literature rarely focuses on how to decouple multi-level transmission powers for devices to guarantee an efficient collided packets decoding with SIC.

In this paper, we extend the decentralized power control framework to address these limitations. We propose a generalized multi-level decentralized power control (MLP-based) scheme for short packet transmission and give the mathematic expression of discrete decentralized transmission powers, for which the number of power levels is decoupled with active devices or users. The main contributions of this work are summarized as follows:

(1) Formulating a general N-level decentralized power control scheme and give the minimum transmission power set to guarantee successful intra-slot SIC decoding for up to multiple collided short packets.

(2) Deriving a closed-form expression for the lower bound of the packet reception probability, which provides clear insights into the impact of the number of power levels N, the number of collided packets l and the packet length n.

(3) Providing numerical results that validate the analytical derivation and comparisons with NOMA-based scheme, which demonstrate that the proposed MLP-based scheme can improve collided packets reception probability.

The remainder of this paper is organized as follows. Section 2 details system model and the proposed multi-level decentralized power control scheme. Section 3 derives the closed-form expression for packet reception probability lower bound. Numerical results and comparisons are presented in section 4. Finally, the paper is concluded and the future work is given in section 5.

2 SYSTEM MODEL AND MULTI-LEVEL DECENTRALIZED POWER CONTROL SCHEME

2.1 System Model

Consider an IoT scenario in which devices communicate with the central base station by using the multi-level decentralized power scheme. We study the case where receiver is capable of handling a maximum of L packets for concurrently transmission or decoding, which means that the receiver can maximally support L collided packets reception.

The transmitted information for all the devices is k-bits and the transmitted information is encoded as n-symbols with coding rate $R = k/n$. Each device randomly selects its transmission power from a common set $\mathbf{E}$. The communication channel we consider in this paper is additive white Gaussian noise channel (AWGN) with being the additive white gaussian noise N_0. At the central base station, the receiver uses the compressed sensing approach [11] to detect active devices (i.e., devices with data transmission at the current time) based on the preamble. If the number of active users is more than L, the transmitted packets don't proceed intra-SIC decoding and cannot be decoded, which will not be discussed in this paper. If the number of active users is no more than L, the central base station decodes the received symbols or packets with intra-slot SIC [12]. Different from infinite length code transmission for wireless communication, the packet error probability should be considered for system performance analysis [13]. Thus, the packet error probability for intra-slot SIC decoding will be considered in the subsequent system performance analysis.

2.2 Multi-level Decentralized Power Control Scheme

The multi-level decentralized power scheme design will be elaborated in detail and the N-level decentralized power control scheme is researched in this subsection. For the N-level decentralized power control scheme, which means that l devices can select transmission powers randomly from transmission power set

$$\mathbf{E} = \{\mathrm{E}_1, ..., \mathrm{E}_N\}, \tag{1}$$

where $N \in \mathbb{N}^*$, to transmit multiple packets simultaneously to central base station with $\mathrm{E}_1 < ... < \mathrm{E}_N$. Generally, we call the transmission power $\mathrm{E}_i \in \mathbf{E}$ as i-th level transmission power and $i \in \mathscr{N} \triangleq \{1, 2, ..., N\}$, which is the set denoting different transmission power levels. When these devices select different transmission powers, the central base station can recover the collided packets based on intra-slot SIC in one slot with the packet error probability $\varepsilon \leq \varepsilon^*$, in which ε^* is the system tolerable maximum packet error probability.

Consider the case that the central base station can maximally support $L(2 \leq L \leq N)$ collided packets reception based on intra-slot SIC in one slot. In order to guarantee the L-collided packets to be recovered with $\varepsilon \leq \varepsilon^*$ by intra-slot SIC decoding processing, the selected transmission powers $\{e_i | i = 1, 2, ..., L\}$ by transmitted packets need to meet

$$\gamma^* \geq \frac{e_L}{\sum_{i=1}^{L-1} e_i + \mathrm{N}_0}, ..., \gamma^* \geq \frac{e_1}{\mathrm{N}_0} \tag{2}$$

with $e_L > e_{L-1} > ... > e_1$ and γ^* being the decoding threshold for short packet and N_0 being the additive white gaussian noise. By [3][10] the decoding threshold γ^* for short packet can be written as

$$\left\{\begin{array}{l}\gamma^* = 2^{R^*} - 1 \\ R^* = \frac{Q^{-1}(\varepsilon^*)\sqrt{\log_2 e}}{\sqrt{n}} + R,\end{array}\right. \tag{3}$$

where n is the length of the transmitted packet and $R = k/n$ is the coding rate and ε^* is the system tolerable packet error probability for the short packet. Owing to transmission powers randomly selected from **E**, the minimum transmission power set need to meet

$$\gamma^* = \frac{\mathrm{E}_{L+j}}{\sum_{i=j+1}^{L+j-1}\mathrm{E}_i + \mathrm{N}_0}, ..., \gamma^* = \frac{\mathrm{E}_{j+1}}{\mathrm{N}_0} \tag{4}$$

where $j \in \{0, 1, ..., N-L\}$. By Eq.(4), the minimum transmission power set which can support L-collision packets reception can be derived as

$$\mathrm{E}_i = \left\{\begin{array}{l}\mathrm{N}_0\gamma^*(\gamma^*+1)^{L-1}, 1 \le i \le L \\ \gamma^*\left(\sum_{k=i-L}^{i-1}\mathrm{E}_k + \mathrm{N}_0\right), L < i \le N.\end{array}\right. \tag{5}$$

3 PACKET RECEPTION PROBABILITY WITH DECENTRALIZED POWER CONTROL SCHEME

This section will derive the closed-form expression of packet reception probability with decentralized power control scheme. According to section 2, the packet reception probability is related with coding rate R, packet length n and transmission power set **E** with N elements. Owing to the coding rate $R = k/n$ and k which is the transmitted information being fixed for periodic traffic of the same type in IoT scenarios [14], the packet length and transmission power set will be the mainly analyzed factors in this paper. Define the packet reception probability function as $D(l, n, N)$, in which l is the number of collided packets. It is obvious that the collided packets cannot be recovered within ε^* when $l > L$ by Eq. (2)(3)(4). Thus, we just give the closed-form expression for packet reception probability for $l \le L$.

Case 1: When $l = 1$, the packet reception probability for single packet transmission can be derived as

$$D(l, n, N) = 1 - \frac{1}{N}\sum_{a_1=1}^{N}\varepsilon_1^{\left(\mathrm{E}_{a_1}\right)}, \tag{6}$$

where

$$\left\{\begin{array}{l}\varepsilon_1^{\left(\mathrm{E}_{a_1}\right)} = Q\left(f\left(\gamma_1^{\left(\mathrm{E}_{a_1}\right)}, n, R\right)\right) \\ \gamma_1^{\left(E_{a_1}\right)} = \mathrm{E}_{a_1}/\mathrm{N}_0\end{array}\right. \tag{7}$$

with $a_1 \in \mathscr{N}$.

Case 2: When $2 \le l \le L$, the collided packets are likely to be recovered within ε^* only if the selected transmission powers of l collided packets are not the same. Otherwise, it cannot. Thus, we consider the case where the selected transmission powers of the l packets are not the same. Let $\mathrm{E}_{a_1},...,\mathrm{E}_{a_l}$ denote the selected transmission powers for the l collided packets with $a_1 < ... < a_l$. By SIC decoding processing, the packet with transmission power E_{a_l} is decoded first and the packet with transmission power $\mathrm{E}_{a_{l-1}}$ is decoded subsequently. The decoding proceeds until the packet with transmission power E_{a_1} is recovered. Packet reception probability for the the packet with transmission power E_{a_i} can be derived as

$$s_i^{\left(\mathrm{E}_{a_i}\right)} = 1 - \varepsilon_i^{\left(\mathrm{E}_{a_1},...,\mathrm{E}_{a_i}\right)} = 1 - Q\left(f\left(\gamma_i^{\left(\mathrm{E}_{a_1},...,\mathrm{E}_{a_i}\right)}, n, R\right)\right) \tag{8}$$

where

$$\gamma_i^{\left(\mathrm{E}_{a_1},...,\mathrm{E}_{a_i}\right)} = \mathrm{E}_{a_i} \Big/ \left(\sum\nolimits_{j=1}^{i-1} \mathrm{E}_{a_j} + \mathrm{N}_0\right)$$

with $a_i \in \mathscr{N}\,(1 \le i \le l)$.

The probability for all the l collided packet to be recovered within ε^* can be derived as

$$\begin{aligned} D\left(l,n,N\right) &= \Pr\left\{a_1 \ne ... \ne a_l\right\} \times \frac{l!}{\mathrm{A}_N^l}\left(\sum\nolimits_{a_1=1}^{N-l+1} \cdots \sum\nolimits_{a_l=l}^{N} \prod\nolimits_{i=1}^{l} s_i^{\left(\mathrm{E}_{a_i}\right)}\right) \\ &= \frac{\mathrm{A}_N^l}{N^l} \times \frac{l!}{\mathrm{A}_N^l}\left(\sum\nolimits_{a_1=1}^{N-l+1} \cdots \sum\nolimits_{a_l=l}^{N} \prod\nolimits_{i=1}^{l} s_i^{\left(\mathrm{E}_{a_i}\right)}\right) \\ &= \frac{l!}{N^l}\left(\sum\nolimits_{a_1=1}^{N-l+1} \sum\nolimits_{a_2=2}^{N-l+2} \cdots \sum\nolimits_{a_l=l}^{N} \prod\nolimits_{i=1}^{l} s_i^{\left(\mathrm{E}_{a_i}\right)}\right), \end{aligned} \tag{9}$$

in which $\Pr\{X\}$ denotes the probability that the event X occurs, A_N^l is the number of permutation for selecting l factors from N factors and $l!$ is the factorial of l. By Eq. (3)(4), the lower bound for Eq. (8) can be derived as

$$s_i^{\left(\mathrm{E}_{a_i}\right)} = 1 - \varepsilon_i^{\left(\mathrm{E}_{a_1},...,\mathrm{E}_{a_i}\right)} \ge 1 - \varepsilon^* \triangleq s^*. \tag{10}$$

Further, the lower bound of packet reception probability $D(l,n,N)$ for l collided packets can be given as

$$\begin{aligned} D\left(l,n,N\right) &= \frac{l!}{N^l}\left(\sum\nolimits_{a_1=1}^{N-l+1} \sum\nolimits_{a_2=2}^{N-l+2} \cdots \sum\nolimits_{a_l=l}^{N} \prod\nolimits_{i=1}^{l} s_i^{\left(\mathrm{E}_{a_i}\right)}\right) \\ &\ge \frac{\mathrm{C}_N^l l!}{N^l}\left(1-\varepsilon^*\right)^l \triangleq D^*\left(l,n,N\right), \end{aligned} \tag{11}$$

in which C_N^l is the number of combination for selecting l factors from N factors.

By Eq. (6)(7), it can be known that lower bound expression of reception probability $D^*\left(l,n,N\right)$ for l collided packets still holds for $l = 1$. Thus, the closed-form expression of reception probability lower bound for l collided packets with decentralized power control can be denoted as

$$D^*\left(l,n,N\right) = \frac{\mathrm{C}_N^l l!}{N^l}\left(1-\varepsilon^*\right)^l \tag{12}$$

with $l \in \mathscr{L} \triangleq \{1,2,...,L\}$. It is obvious that the reception probability lower bound $D^*\left(l,n,N\right)$ gives a more clearly mathematic depiction for reception probability of collided packets. By $D^*\left(l,n,N\right)$, we are much easier to analyze the influence of factors l, n and N on packet reception probability.

4 Numerical Analysis

In this section, the numerical analysis of reception probability for multiple short collided packets with decentralized power control is given. Firstly, the numerical and simulation results are provided to verify the closed-form expression of reception probability lower bound for l collided packets. Besides, the influence of N, l and n on collided packets reception probability is analyzed in section 4.1. Secondly, the comparison between different decentralized power control schemes is provided to demonstrate the superiority of the proposed multi-level decentralized power control scheme in section 4.2.

4.1 Reception Probability for Multi-packet Reception

The simulation results for Eq. (11) and numerical results for Eq. (12) are shown in Fig. 1, from which it can be demonstrated that the derived closed-form expression Eq. (12) is the lower bound for l collided packets with decentralized power control. For $D^*(l,n,N)$, it is a single-variable function of N and can be rewritten as $D^*(N)$ when the packet length n and the number of collided packets l are determinate. In order to analyze the influence of N on reception probability, we define the continuous function $D_{\mathrm{c}}^*(N)$ to be the continuous extension of the discrete function $D^*(N)$. The first derivatives of $D_{\mathrm{c}}^*(N)$ and $D^*(N)$ can be derived as

$$\begin{aligned}
&\frac{dD_{\mathrm{c}}^*(N)}{dN} = \left[\frac{N!}{(N-l)!N^l}(1-\varepsilon^*)^l\right]' = (1-\varepsilon^*)^l\left[\frac{N!}{(N-l)!N^l}\right]' \xrightarrow{(x!)'=\Gamma(x+1)\Psi(x+1)=x!\Psi(x+1)} \\
&= \frac{(1-\varepsilon^*)^l N^{l-1} N!(N-l)!}{[(N-l)!N^l]^2}\left[N(-\gamma_0+\Psi(N+1)) - N(-\gamma_0+\Psi(N-l+1)) - l\right] \\
&\xrightarrow{\text{For } N\in\mathcal{N}=\{1,2,\dots,N\},\Psi(x+1)=(-\gamma_0+f(x))} \\
&\frac{dD^*(N)}{dN} = \frac{(1-\varepsilon^*)^l N^{l-1} N!(N-l)!}{[(N-l)!N^l]^2}\left[\sum\nolimits_{i=N-l+1}^{N}\frac{N}{i} - l\right] \\
&\geqslant \frac{(1-\varepsilon^*)^l N^{l-1} N!(N-l)!}{[(N-l)!N^l]^2}\left[\sum\nolimits_{i=N-l+1}^{N}\frac{N}{N} - l\right] = 0
\end{aligned} \tag{13}$$

with

$$\begin{cases}\Gamma(x) = \int_0^x t^{x-1}e^{-t}dt = (x-1)! \\ \Psi(x) = [\ln\Gamma(x)]' = \Gamma'(x)/\Gamma(x)\end{cases},$$

in which with $f(x)$ is the harmonic function of x, γ_0 is the Euler-Mascheroni constant. By Eq. (13), it can be seen that $D^*(N)$ is an increasing function of N for certain l and n. Thus, we can see from Fig. 1 that the reception probability for collided packets is higher with the number of transmission power levels N increasing for determined collided packets l and packet length n. It means that $D^*(N)$ can be improved by increasing transmission powers levels of transmission power set $\mathbf{E}$.

Similarly, for a certain transmission power set and packet length, the $D^*(l,n,N)$ can be rewritten as $D^*(l)$, which is a single-variable function of l. We also define the continuous function $D_{\mathrm{c}}^*(l)$ to be the continuous extension of discrete function $D^*(l)$. For $D_{\mathrm{c}}^*(l)$ and $D^*(l)$, their first derivatives can be derived as

$$\begin{aligned}
&\frac{dD_{\mathrm{c}}^*(l)}{dl} = \left[\frac{N!}{(N-l)!N^l}(1-\varepsilon^*)^l\right]' = N!\left[\frac{(1-\varepsilon^*)^l}{(N-l)!N^l}\right]' \\
&= \frac{N!}{\left[(N-l)!N^l\right]^2}A_1 \xRightarrow{(x!)'=\Gamma(x+1)\Psi(x+1)=x!\Psi(x+1)} \\
&= \frac{N!(1-\varepsilon^*)^l}{\left[(N-l)!N^l\right]^2}(A_2+A_3) \xRightarrow{\text{For } N\in\mathcal{N}=\{1,2,\ldots,N\},\Psi(x+1)=(-\gamma_0+f(x))} \\
&\frac{dD^*(l)}{dl} = \frac{N!(N-l)!N^l(1-\varepsilon^*)^l}{\left[(N-l)!N^l\right]^2}A_4 \xRightarrow{f(x)=\gamma_0+\ln x} \\
&= \frac{N!(N-l)!N^l(1-\varepsilon^*)^l}{\left[(N-l)!N^l\right]^2}\left[\ln(1-\varepsilon^*) - \sum_{i=N-l+1}^{N}\frac{1}{i}\right] < 0
\end{aligned} \tag{14}$$

with

$$\begin{cases}
A_1 = (1-\varepsilon^*)^l\ln(1-\varepsilon^*)(N-l)!N^l - (1-\varepsilon^*)^l\left[(N-l)!N^l\right]' \\
A_2 = \ln(1-\varepsilon^*)(N-l)!N^l \\
A_3 = (N-l)!(-\gamma_0+\Psi(N-l+1))N^l - (N-l)!N^l\ln N \\
A_4 = \ln(1-\varepsilon^*) - \gamma_0 + f(N) - \sum_{i=N-l+1}^{N}\frac{1}{i} - \ln N.
\end{cases} \tag{15}$$

By Eq. (14), we can see that the $D^*(l)$ is an decreasing function of l for certain N and n. Thus, the reception probability decreases when the number of collided packets increases for certain N and n as Fig. 1 shows.

Further, we explore the influence of n on collided packets reception probability as Fig. 2 shows, in which we can see that the $D^*(l,n,N)$ is increasing as n increases. The reason for this phenomenon is that packet error probability ε^* will be more and more smaller as blocklength n increases, which will bring more higher collided packets reception probability according to Eq. (12). Moreover, we define $D(l,\infty,N)$ as the collided packets reception probability for infinite blocklength transmission and $\mathbf{E}_\infty$ as transmission power set with N elements for infinite blocklength, which is a particular case of $\mathbf{E}$ by Eq.(3)(4)(5). For infinite blocklength transmission, the packet error probability will be regarded as 0 and the collided packets will be recovered only if the selected transmission powers from $\mathbf{E}_\infty$ are different. Thus, the $D(l,\infty,N)$ can be derived as

$$D(l,\infty,N) = \frac{\mathrm{A}_N^l}{N^l} = \frac{\mathrm{C}_N^l\, l!}{N^l}. \tag{16}$$

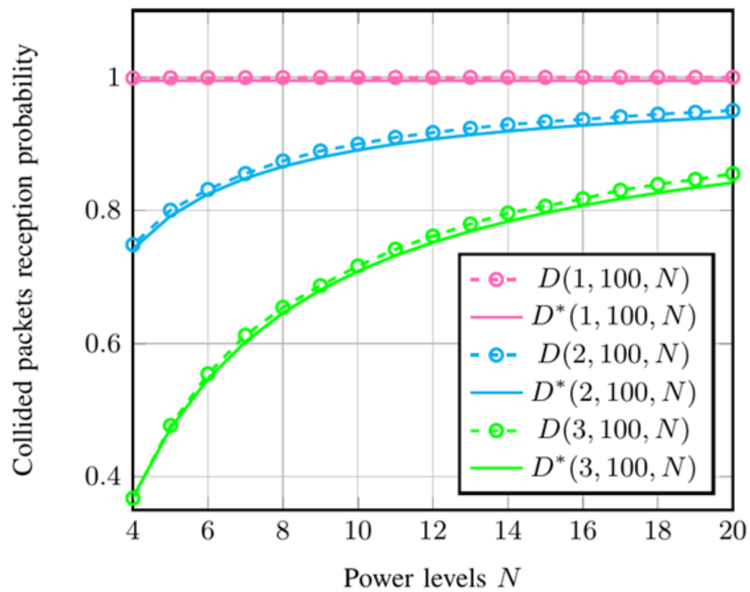

Fig. 1. Collided packets reception probability for $L = 3, R = 1, \varepsilon^* = 10^{-2}$

By Eq. (12), it is obvious that $\lim_{n\to\infty} D^*(l,n,N) = D(l,\infty,N)$ under the same average packet transmission power $\overline{\mathrm{P}}$ as Fig. 2 shows.

4.2 Comparison between Different Decentralized Power Control Schemes

The literature [9] proposed a decentralized power control scheme for infinite blocklength transmission, which is based on NOMA. In this subsection, we use NOMA-based to denote the proposed decentralized power control scheme in [9] and expand this designed scheme to finite blocklength transmission (i.e., short packet transmission) to explore its performance. Besides, we use MLP-based to denote the proposed multi-level decentralized power control scheme in this paper. At the same, we define D_{NOMA} to describe the collided packets reception probability for NOMA-based scheme in [9] under the same average packet transmission power with the proposed MLP-based scheme.

The comparison between NOMA-based decentralized power control scheme and the proposed decentralized power control scheme is given as Table 1 shows. It can be seen the collided packets reception probability of the proposed multi-level decentralized power control scheme in this paper has a superior performance when compared with the NOMA-based decentralized power control scheme whenever for infinite blocklength and finite blocklength transmission. Specifically, the collided packets reception probability for $L = 3, n = 100$ can be significantly improved from 0.176 to 0.712 by adjusting the transmission power levels of $\mathbf{E}$. Likewise, the collided packets reception

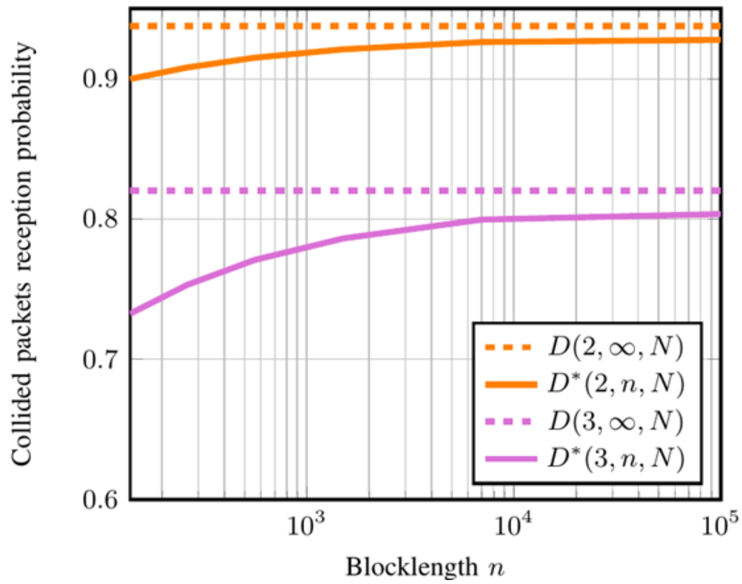

Fig. 2. Collided packets reception probability for $L=3, R=1, \varepsilon^*=10^{-2}, \overline{\mathrm{P}}=26\mathrm{dBm}, \mathrm{N}_0=0\mathrm{dBm}$

probability for infinite blocklength transmission can also have a significant improvement for $L=3$ as Table 1 shows, in which we can see the reception probability increases from 0.220 to 0.902.

5 Conclusion and Future Work

This paper proposes a multi-level decentralized power control (MLP-based) scheme tailored for short packet transmission in grant-free random access systems. By decoupling the number of power levels from the number of active devices, the proposed scheme facilitates efficient intra-slot SIC decoding of collided packets, whether for a finite or an infinite blocklength transmission. In addition, the paper derived a closed-form lower bound for the packet reception probability, which clearly reflects the influence of the number of power levels, the number of collided packets and the packet length on packet reception probability. Numerical results confirmed the validity of the derived expression and demonstrated that the MLP-based scheme outperforms the existing NOMA-based decentralized power control scheme in terms of reception probability both for finite and infinite blocklength. The proposed framework provides a foundational approach for enhancing collision resolution in mMTC systems with short packets.

From section 4, it can be seen that the proposed multi-level decentralized power control scheme can significantly improve collided packets reception probability. However, on the one hand, hardware complexity of the receiver and energy consumption will increase with N being larger, which will improve collided packets reception probability. On the other hand, the channel model we con-

Table 1: Packet reception probability for MLP-based and NOMA-based schemes with short packet transmission parameters being $R = 1, \varepsilon^* = 10^{-1}, \mathrm{N}_0 = 0\mathrm{dBm}$

L	n	MLP-based N	MLP-based $D^*(L,n,N)$	NOMA-based $D^*(L,n,N)$
2	100	10	0.873	0.430
		20	0.934	
	∞	20	0.950	0.500
3	100	10	0.569	0.176
		30	0.712	
	∞	30	0.902	0.220

sider in this paper is AWGN, which is the theoretical foundation and the performance benchmark for research on other fading channels. How to get trade-off among collided packets reception probability, hardware complexity of the receiver, energy consumption is our subsequently investigation as well as performance analysis under different fading channel models and path loss models.

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Declaration on Generative AI

During the preparation of this work, the authors only used DeepSeek to check grammar and spelling. After using the tool, the authors reviewed and edited the content as needed and take full responsibility for the publication's content.

References

[1] Shi Z, Gao W, Liu J, Kato N, Zhang Y. Distributed Q-Learning-Assisted Grant-Free NORA for Massive Machine-Type Communications. In: Proceeding of IEEE Global Communications Conference (GLOBECOM'20). Piscataway, NJ, USA: IEEE; 2020. p. 1-5.

[2] Ding J, Qu D, Jiang H, Jiang T. Success probability of grant-free random access with massive MIMO. IEEE Internet Things J. 2019 Feb;6(1):506-16.

[3] Tian N, Changle L, Cheng J, Yue W, Luo M. Decentralized power control for an ALOHA-type random multiple access system with short packet transmission. Wireless Commun Mobile Comput. 2022 Jul;2022:1-10.

[4] Xu C, Ping L, Wang P, Chan S, Lin X. Decentralized power control for random access with successive interference cancellation. IEEE J Sel Areas Commun. 2013 Nov;31(11):2387–2396.

[5] Lin H, Ishibashi K, Shin WY, Fujii T. Decentralized power allocation for secondary random access in cognitive radio networks with successive interference cancellation. In: Proceeding of IEEE International Conference on Communications (ICC'16). Piscataway, NJ, USA: IEEE; 2016. p. 1-6.

[6] Fan W, Fan P, Ding Z. On the throughput of NOMA-ALOHA in massive IoT with sparse active users. IEEE Wireless Commun Lett. 2024 Mar;13(3):582–586.

[7] Jin Y, Lee TJ. Throughput analysis of NOMA-ALOHA. IEEE Trans Mobile Comput. 2022 Apr;21(4):1463–1475.

[8] Ryu WJ, Lee JM, Kim DS. Multi-agent quantum reinforcement learning for adaptive transmission in NOMA-based irregular repetition slotted ALOHA. IEEE Open J Commun Soc. 2025 Apr;6:4405–4420.

[9] Shao X, Sun Z, Yang M, Gu S, Guo Q. NOMA-based irregular repetition slotted ALOHA for satellite networks. IEEE Commun Lett. 2019 Apr;23(4):624–627.

[10] Polyanskiy Y, Poor HV, Verdu S. Channel coding rate in the finite blocklength regime. IEEE Trans Inf Theory. 2010 May;56(5):2307–2359.

[11] Wang J, Zhang Z, Hanzo L. Joint active user detection and channel estimation in massive access systems exploiting Reed-Muller sequences. IEEE J Sel Topics Signal Process. 2019 Jun;13(3):739–752.

[12] Interdonato G, Pfletschinger S, Vázquez-Gallego F, Alonso-Zarate J, Araniti G. Intra-slot interference cancellation for collision resolution in irregular repetition slotted ALOHA. In: Proceeding of IEEE International Conference on Communication Workshop (ICCW'15). Piscataway, NJ, USA: IEEE; 2015. p. 2069-74.

[13] Durisi G, Koch T, Popovski P. Toward massive, ultrareliable, and low-latency wireless communication with short packets. Proc IEEE. 2016 Sep;104(9):1711-26.

[14] Finn N. Introduction to Time-Sensitive Networking. IEEE Commun Stand Mag. 2022 Jan;6(4):8-13.