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Research Article

Decentralized Power Control for an ALOHA-Type Random Multiple Access System with Short Packet Transmission

Ni Tian,[1] **Changle Li**,[1] **Jun Cheng**,[2] **Wenwei Yue**,[1] **and Maofeng Luo**[1]

[1]*State Key Laboratory of Integrated Services Networks, Xidian University, Xi'an, Shaanxi 710071, China*
[2]*Department of Intelligent Information Engineering and Science, Doshisha University, Kyoto 6008586, Japan*

Correspondence should be addressed to Changle Li; clli@mail.xidian.edu.cn

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Machine to machine communication is an important scenario in a 6G communication network. Random multiple access has recently been revisited and considered a key technology for machine to machine communication scenarios due to many advantages such as without coordination setup time. It is a regret that packet collision probability will be extremely higher for random multiple access when massive devices randomly accessing base station. Decentralized power control is an efficient scheme in random multiple access systems which can support intraslot successive interference cancellation to recover multiple collided packets at receivers. However, existing studies of decentralized power control for random multiple access are with the assumption that blocklength of transmitted packets is infinite, which neglects that machine to machine communication is characterized by finite blocklength transmission (i.e., short packet) in 6G. This paper focuses decentralized power control with short packet transmission in random multiple access systems. First, the closed-form expression of signal to interference plus noise ratio (SINR) threshold for short packets is derived. Then, decentralized transmission power profile is defined based on derived SINR threshold of short packets, which can support intraslot successive interference cancellation deciding at receivers for an ALOHA-type random multiple access system. Further, we propose derivation method to maximize system throughput, which can reduce optimization cost. Theoretical findings in this paper can provide valuable benchmark for short packet transmission with decentralized power control in random multiple access systems.

1. Introduction

Machine to machine communication is a typical communication scenario in 6G network [1–5]. In machine-type communication scenarios, a massive amount of wireless communication devices transmit short packets sporadically to base station [6–8], in which coordinated access protocols is inefficient owing to prohibitively large overhead and delay. An uncoordinated access method, i.e., random multiple access systems, has attracted more and more attention in recent years [9–11] and has been regarded as a promising technology for machine-type communication scenario due to its simplicity and flexibility.

However, collision probability will be higher for random multiple access systems when tremendous devices access the base station. The collided packets are discarded for conventional random multiple access systems, such as slotted ALOHA and diversity slotted ALOHA [12], which will lead to system performance degradation and limit the development of random multiple access systems. The accession of successive interference cancellation (SIC) technology infuses new vitality to slotted ALOHA type random multiple access systems. At a transmitter, all the devices can transmit replicas of the same packets randomly, embedding the access information of slots. Thereby, if one of the replicas can be resolved, the other replicas' accessing position can be found and can be removed from the other slots via SIC at receivers as shown in Figure 1, which can be called as interslot SIC.

The benefit brought from SIC is that it can turn some collided slots into single slots and solve the destructive collision problem for slotted ALOHA-based random multiple access systems [13]. Thus, the accession of SIC technology

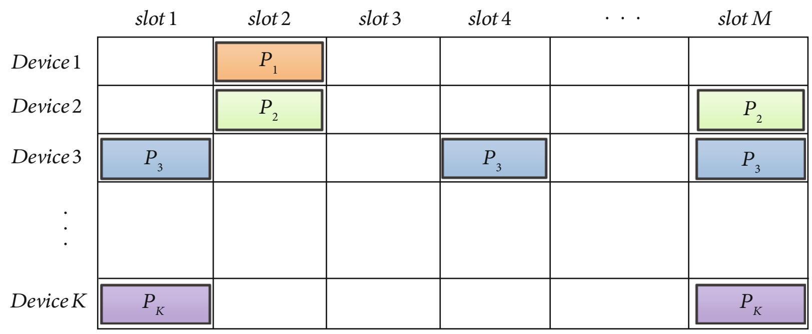


Figure 1: An example of Slotted ALOHA protocol based on SIC: packet p_3 can be resolved in slot 4, and the replica p_3 of can be removed from slot 1 and slot M. Now, in slot 1, there is only packet p_K and it can be resolved. Meanwhile, the replicas of packet p_K can be eliminated from slot M. Thus, $p_2$can be recovered. At the same way, packet p_2 and its replicas can removed from slot 2. Finally, there is only packet p_1 in slot 2, and it can be recovered.

at receivers can dramatically improve the capability of slotted ALOHA-based random multiple access systems, which inspires a series of works that applied various concepts to design SIC-based random multiple access systems [14–17]. Contention resolution diversity slotted ALOHA (CRDSA) was proposed in [14] and first applied SIC technology to resolve packet collision problem of random multiple access systems, which can gain greatly improvement of system throughput. On the foundation of CRDSA, [15] proposed irregular repetition slotted ALOHA (IRSA), in which system performance can be further improved over CRDSA by optimizing packet transmission distribution at transmitter. As extension of IRSA, coded slotted ALOHA (CSA) was proposed in [16, 17] and allowed packet transmission in IRSA system with supportable rates by substituting generic linear block for repetition codes.

However, all the above system performance analysis is only considering to apply SIC among slots (i.e., interslot SIC) to turn the collision slots to singleton slots in a collision model, for which a packet can be revolved only if no other packets is transmitted concurrently. To be frank, it does not essentially solve the problem of collided packet recovery. Multipacket reception (MPR) [18–20] has been studied for multiple packet recovery from a collision. Capture effect and intraslot SIC are the main methods of MPR to be used to recover multiple packets [21] for random multiple access systems.

Capture effect was proposed in [22], with which one of collided packets is decoded independently by treating other collided signals as background noise and can be recovered only if its received signal to interference plus noise ratio (SINR) exceeds a certain threshold. In [23]; the Rayleigh block fading channel was considered for packets transmission in IRSA system, and fading can bring power variation of signal in collision slots. Thus, capture effect was used to resolve collided packets in one slot, which can gain a remarkable throughput that is over 1 [packet/slot] for a target PEP less than 10^{-2}. Unfortunately, the method that using capture effect to recover multiple packets in collided slots is not applicable for medium and high rate scenarios [24]. Aiming at medium and high rate scenarios, decentralized power control is proposed to support intraslot SIC for multiple packet recovery in random multiple access systems [24–27]. Decentralized power control means that there is no cooperation among devices for transmission power selection as well as transmission power allocation or control by central station. Each device can randomly select its transmission power according to its certain rules and without coordination with other devices. [25] first proposed a decentralized power control scheme, in which a transmission power profile specified by a transmission power distribution was defined and regarded as transmission power selection for all the devices. The proposed decentralized power control scheme in [25] can dramatically simplify communication system complexity and is the targeted decentralized power control scheme design this paper focuses on. Further, [25] first proved that the optimal power distribution of decentralized power control which can support intraslot SIC at receivers is discrete and derived the minimum transmission power profile for intraslot SIC. The numerical results in [25] demonstrated that the intraslot SIC supported by decentralized power control to recover multiple packets can obtain superior system performance when compared with a capture effect method. [27] further extended the work that using intraslot SIC supported by decentralized power control in [25] to recover multiple packets to a generalized channel-aware scheme, with which different transmission powers can be used by each device with a certain probability based on its own channel state information. It can be seen that with the decentralized power control proposed in [25], intraslot SIC can improve the capability of random multiple access systems. Although some literatures are making more efforts on multiple packet recovery with intraslot SIC supported by decentralized power control in random multiple access systems, these studies are with the assumption that transmitted packets are infinite blocklength, which ignore the fact that machine-type communication scenarios are characterized by short packets (i.e., finite blocklength) [28].

Distinguishing from infinite blocklength transmission that packet error probability (PEP) can be dealt with 0 for its SINR exceeding a given threshold; PEP for finite blocklength transmission still needs to be considered although its SINR is more than the given threshold. PEP for finite blocklength transmission is a necessary factor for system design and optimization [29]. It is a regret that a series of theories for short packet transmission have been developed recent years, and there are many theories about short packets that need to be filled and advised. Especially, there are no related theories for signal to interference plus noise power ratio of short packet recover which can support decentralized power control, which limits existing researches to focus on decentralized power control of short packets. In addition, system optimization of short packet transmission is more complex due to the introduced PEP when compared with infinite blocklength transmission. Hence, it is important to develop related theory about signal to interference plus noise power ratio of short packet recover to support decentralized power control scheme to recover multiple packets in collided slots for random multiple access systems. Meanwhile, it is a worthwhile problem to investigate how to analyse and optimize system performance of short packet transmission with decentralized power control scheme.

In this paper, we focus on decentralized power control scheme of short packets in an ALOHA-type random multiple access system. To enhance the ALOHA-type random multiple access performance, decentralized transmission power profile specified by SINR threshold of short packet transmission is essential. Thus, this paper first derives closed-form expression of signal to interference plus noise ratio (SINR) threshold of short packets. Then, considering intraslot SIC decoding to recover multiple collided packets at receivers, decentralized transmission power profile is specified by the derived SINR threshold of short packets. Subsequently, system performance of an ALOHA-type random multiple access system for short packet transmission is analysed. Meanwhile, this paper proposes convex optimization and derivation methods to maximize system performance of short packet transmission. The main contributions of the paper are summarized as follows:

(i) The closed-form expression of SINR threshold for short packets is derived in this paper, which is first proposed to our best knowledge. Based on the SINR threshold, an efficient decentralized transmission power profile for short packet transmission can be obtained, which can enhance system performance

(ii) The ALOHA-type random multiple access system performance for short packet transmission is analysed thoroughly, in which we convert system throughput optimization problem into a convex problem. Hence, maximum system throughput can be obtained by a convex optimization method, which dramatically decreases difficulty of optimizing system throughput

(iii) For the higher average transmission power case, the derivation method is proposed to optimize system throughput in this paper, which can further reduce complexity of maximum system throughput achievement

The organization of the rest paper is as follows: Section 2 describes designed intraslot SIC scheme for finite blocklength transmission, which presents the derived SINR threshold and transmission power profile for short packet transmission. The system model of short packet transmission as well as system throughput optimization is given in Section 3. The numerical results are presented in Section 4 to demonstrate the proposed intraslot SIC scheme for finite blocklength transmission and system performance optimization can improve system throughput of short packet transmission. Section 5 concludes the paper work and gives a future work of short packet transmission for random multiple access systems.

2. Intraslot SIC Scheme Support for Finite Blocklength Transmission

Consider the case that two packets can be concurrently transmitted and give transmission power function to support intraslot SIC scheme at receivers for short packet transmission.

According to [29, 30], the probability that the transmitted finite blocklength can be recovered is $1-\epsilon$, in which ϵ is the packet error probability (PEP) and is given as Equation (1). The PEP for finite blocklength is related with blocklength n as well as SINR γ and coding rate R and is given as

$$\epsilon = Q(f(\gamma, n, R)), \tag{1}$$

with

$$\begin{aligned} f(\gamma, n, R) &= \frac{C(\gamma)-R}{\sqrt{V(\gamma)/n}}, \\ C(\gamma) &= \log_2(1+\gamma), \\ V(\gamma) &= \left(1-\frac{1}{(1+\gamma)^2}\right)\log_2 e. \end{aligned} \tag{2}$$

Assume that all the transmitted packets are with the same blocklength n and coding rate R. For a type-2 collision slot with transmission power level and noise power level, the probability that the two transmitted short packets are decoded successfully by SIC technology can be derived as

$$P_{\text{suc}} = \begin{cases} 1-Q\left(f\left(\gamma_2^{i,j}, n, R\right)\right), \\ \left(1-Q\left(f\left(\gamma_2^{i,j}, n, R\right)\right)\right)\left(1-Q\left(f\left(\gamma_2^{0,i}, n, R\right)\right)\right), \end{cases} \tag{3}$$

with

$$\begin{aligned} \gamma_2^{i,j} &= \frac{E_j}{E_i+N_0}, \left(E_j > E_i\right), \\ \gamma_2^{0,i} &= \frac{E_i}{N_0}. \end{aligned} \tag{4}$$

Differing from the infinite blocklength transmission, the probability that the residual short packet is decoded successfully also depends on the SINR of the recovered packet besides its own SNR. Hence, we define $Q(f(\gamma_2^{0,i}, n, R))$ as conditional PEP (CPEP) for the residual packet in type-2 collisions.

From Equation (4), it can be seen that the transmission power is a crucial factor to recover transmitted collided packets. We define transmission power profile $\mathbf{E} = \{E_i \mid i = 0, 1, 2, \cdots\}$ as

$$E_i = \begin{cases} 0, & i = 0, \\ \phi'(E_{i-1}), & i > 0, \end{cases} \tag{5}$$

with

$$\phi\left(e'\right) = \gamma^*\left(e' + N_0\right), \tag{6}$$

where γ^* is SINR threshold for short packet decoding. Differing from SINR threshold being $2^R - 1$ for infinite blocklength transmission in [25], γ^* is related with PEP ϵ, blocklength n besides coding rate R.

From Equation (1), γ^* can be expressed as

$$\frac{\log_2(1+\gamma^*) - R}{\sqrt{1 - \left(1/(1+\gamma^*)^2\right)}} = \frac{Q^{-1}(\epsilon)\sqrt{\log_2 e}}{\sqrt{n}}. \tag{7}$$

The analytical expression for γ^* cannot be derived by Equation (7). We observed that $\sqrt{1 - 1/(1+\gamma^*)^2}$ approaches 1 when γ^* is higher. Hence, we approximate γ^* as Equation (8) for higher SINR, with which PEP of the length-n and rate-R transmitted packet can be controlled within ϵ.

$$\begin{cases} \gamma^* \approx 2^{R^*} - 1, \\ R^* = \dfrac{Q^{-1}(\epsilon)\sqrt{\log_2 e}}{\sqrt{n}} + R. \end{cases} \tag{8}$$

The $\gamma^* \longrightarrow 2^R - 1$ and $\phi(e') = (2^R - 1)(e' + N_0)$ when n approaches infinity, which is the same with Equation (8) ([25]) (see Figure 2).

It is obvious that γ^* is an increasing function with respect to R for a given PEP ϵ, blocklength n according to Equation (7).We can see that $\gamma^*$is smaller when $R < 1$ especially for short packet transmission such as $n \in [100, 2000]$ from Figure 3. Owing to the derived closed-form expression of SINR threshold for higher γ^* with approximate $\sqrt{1 - 1/(1+\gamma^*)^2} \approx 1$, there will be more lager error between real SINR in Equation (7) and approximate SINR in Equation (8) for a smaller γ^* (see Figure 3 for $R < 1$) when compared with $R \geq 1$, which will influence system analysis subsequently. Hence, we just consider the case that $R \geq 1$ for the subsequent system analysis.

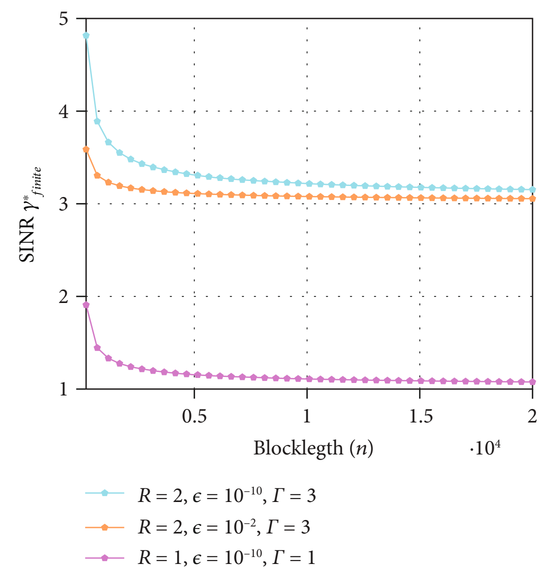


Figure 2: Function $\gamma^*_{\text{finite}} = F(\epsilon, n, R)$ for $\Gamma = 2^R - 1$: for $R = 2, \epsilon = 10^{-10}$, γ^*_{finite} decreases with n increasing. For $R = 2, n = 10000$, γ^*_{finite} decreases with ϵ decreasing. For $\epsilon = 10^{-10}, n = 10000$, γ^*_{finite} decreases with R decreasing. When blocklength n approaches infinity, γ^*_{finite} closes to infinite SINR threshold $\gamma^* = 2^R - 1$.

3. System Model

3.1. System Model. Consider the communication scenario that K active devices share the spectrum hole by a random access manner with proposed intraslot SIC scheme support in Section 2. Our discussion in this paper only considers type-2 collisions can be recovered.

Every device has k information bits which are encoded as length-n symbols (also called a packet) $x_i = \{x_{i1}, x_{i2}, \cdots, x_{in}\}(i = 1, 2 \cdots, K)$ with coding rate $R = k/n$ to be transmitted over AWGN channel. Consider the current slot and the received signal y can be given as

$$y = \sum_i \sqrt{e_i} x_i + \eta, \tag{9}$$

where η is a complex additive white Gaussian noise (AWGN) sample with mean zero and variance N_0. Each device randomly draws a transmission power e_i with probability distribution $\mathbf{P} = \{p_0, p_1, \cdots, p_N\}$ over transmission power profile $\mathbf{E} = \{E_0, E_1, \cdots, E_N\}$. E_0 denotes that the packet is not be transmitted and the probability is p_0. We assume that the length of transmitted packets n and coding rate R is the same for all the devices.

We define that system throughput is the average number of recovered packets per slot and it can be given as

$$T = \Pr\{\text{only one user can be recovered}\} + \Pr\{\text{both users can be recovered}\} = T_1 + T_2, \tag{10}$$

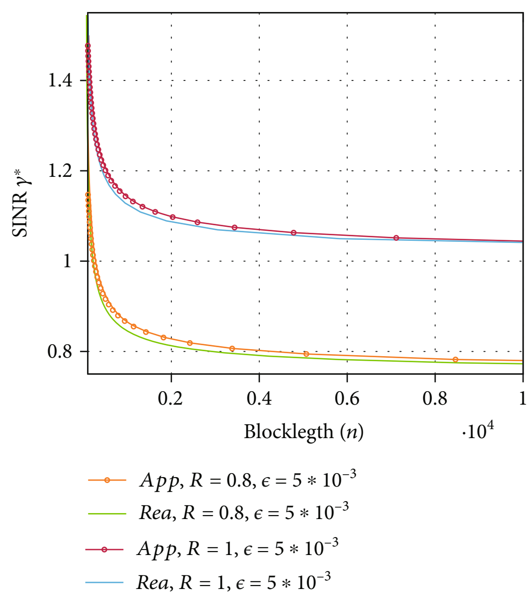


Figure 3: Contrast between real analytical results as Equation (7) and approximate analytical results as Equation (8) for short packet transmission: the greater γ^* is, the more precise the approximate analytical result is. The reason for which is that $\sqrt{1 - 1/(1+\gamma^*)^2}$ more closes to 1 when γ^* is greater. When blocklength $n \longrightarrow \infty$, the approximate analytical SINR threshold $\gamma^* \longrightarrow 2^R - 1$, which is consistent with real analytical SINR threshold for infinite blocklength. Thus, the approximately analytical result is more accurate when blocklength n increases.

where T_1 is the throughput introduced by only one device transmitting and T_2 is the throughput contributed by type-2 collisions.

Different from infinite blocklength decoding by SIC technology in [29], there will be PEP for short packets decoding even the decoding SINR exceeds the given SINR threshold (for details, see Section 2). T_1 and T_2 can be given as

$$\begin{aligned} T_1 &= \Pr\{\text{other users select } E_0\} \\ &\quad * \Pr\{\text{one user selects nonzero power}\} \\ &\quad * \Pr\{\text{the transmitted packet can be recovered}\} \\ &= K p_0^{K-1} \sum_{i=1}^{N} p_i \left(1 - \epsilon_1^{0,i}\right), \end{aligned} \quad (11)$$

$$\begin{aligned} T_2 &= \Pr\{\text{other users select } E_0\} \\ &\quad * \Pr\{\text{two users select different nonzero power}\} \\ &\quad * \begin{bmatrix} \Pr\{\text{one of the transmitted packet can be recovered}\} + \\ \Pr\{\text{the residual packet can be recovered}\} \end{bmatrix} \\ &= \binom{K}{2} p_0^{K-2} * 2 \sum_{j=1}^{N-1} \sum_{k=j+1}^{N} p_j p_k * \left[\left(1 - \epsilon_2^{j,k}\right) + \left(1 - \epsilon_2^{j,k}\right)\left(1 - \epsilon_2^{0,j}\right)\right] \\ &= \binom{K}{2} p_0^{K-2} * 2 \sum_{j=1}^{N-1} \sum_{k=j+1}^{N} p_j p_k \left(1 - \epsilon_2^{j,k}\right)\left(2 - \epsilon_2^{0,j}\right), \end{aligned} \quad (12)$$

with

$$\begin{cases} \epsilon_1^{0,i} = Q\left(f\left(\gamma_1^{0,i}, n, R\right)\right), \\ \epsilon_2^{j,k} = Q\left(f\left(\gamma_2^{j,k}, n, R\right)\right), \\ \epsilon_2^{0,j} = Q\left(f\left(\gamma_2^{0,j}, n, R\right)\right), \end{cases} \quad (13)$$

where $\epsilon_1^{0,i}$ denotes the PEP for the event that one device transmitting with transmission power E_i, $\epsilon_2^{j,k}$denotes PEP of the packet with transmission power E_k for type-2 collisions, and $\epsilon_2^{0,j}$denotes the conditional PEP (CPEP) (see Section 2) of the residual packet with transmission power E_j for type-2 collisions ($E_k > E_j$).

By the transmission power profile **E** defined by Equation (5) in section 2, the decoding SINR at receivers for single packet transmission and type-2 collisions can be derived as

$$\begin{cases} \gamma_1^{0,i} = \dfrac{E_i}{N_0} = \displaystyle\sum_{\nu=1}^{i} (\gamma^*)^{\nu}, \\ \gamma_2^{j,k} = \dfrac{E_k}{E_j + N_0} = \dfrac{\sum_{\nu=1}^{k} (\gamma^*)^{\nu}}{\sum_{\nu=1}^{k} (\gamma^*)^{\nu} + 1}, \\ \gamma_2^{0,j} = \dfrac{E_i}{N_0} = \displaystyle\sum_{\nu=1}^{j} (\gamma^*)^{\nu}. \end{cases} \quad (14)$$

From Equations (11) and (12), the system throughput (the number of packets per available slot) can be expressed by

$$\begin{aligned} T = T_1 + T_2 &= K p_0^{K-1} \sum_{i=1}^{N} \left(1 - \epsilon_1^{0,i}\right) p_i + \binom{K}{2} p_0^{K-2} \\ &\quad * 2 \sum_{j=1}^{N-1} \sum_{k=j+1}^{N} p_j p_k \left(1 - \epsilon_2^{j,k}\right)\left(2 - \epsilon_2^{0,j}\right). \end{aligned} \quad (15)$$

3.2. Throughput Optimization. Compared with infinite blocklength transmission in [25], PEP/CPEP is introduced in system throughput for finite blocklength transmission and it is depends on the selected transmission power, which is embodied by probability distribution $\mathbf{P} = \{p_1, p_2, \cdots, p_N\}$ in Equation (15). Hence, the system throughput can be maximized by probability distribution $\mathbf{P} = \{p_1, p_2, \cdots, p_N\}$. Compared with system throughput optimization for infinite blocklength transmission in [25], system throughput maximization for finite blocklength transmission is not a convex problem with respect to $\{p_i\}_{i>0}$ owing to the accession of $\{\epsilon_2^{j,k}\}_{k>j\geq 0}$ in T_2 for p_0 being given. It can be observed that T_1 is still a convex function of $\{p_i\}_{i>0}$ when p_0 is given [31]. If T_2 can be converted into a convex function, maximizing system throughput is also a convex optimization problem [31].

By Equations (13) and (14), $\{\epsilon_2^{j,k}\}_{k=j+1}$ can be simplified as

$$\begin{cases} \epsilon_2^* = Q\left(f\left(\gamma_2^{j,j+1}, n, R\right)\right), \\ \gamma_2^{j,j+1} = \dfrac{E_{j+1}}{E_j} = \gamma^*, \end{cases} \quad (16)$$

in which γ^* is up to blocklength n, coding rate R, and allowable maximum PEP ϵ. In other words, $\{\epsilon_2^{j,k}\}_{k=j+1}$ is the same and determinate for type-2 collisions with probability pair set $\{(p_j, p_k)\}_{k=j+1}$ over transmission power support pair profile $\{(E_j, E_k)\}_{k=j+1}$.

Moreover, $\epsilon_2^{j,k}(k \neq j+1)$ is smaller owing to enough higher-SINR, which leads to less relation of system throughput to blocklength n, coding rate R, and allowable maximum PEP ϵ for finite blocklength. To highlight influence of n, R, and ϵ on system throughput for finite blocklength transmission, we use ϵ_2^* to approximate $\{\epsilon_2^{j,k}\}_{k\neq j+1}$ forT_2. T_2 can be approximated as

$$\begin{aligned} T_2^{\text{app}} &= \binom{K}{2} p_0^{K-2}(1-\epsilon_2^*)(2-\epsilon_2^*) * 2\sum_{j=1}^{N-1}\sum_{k=j+1}^{N} p_j p_k \\ &= \binom{K}{2} p_0^{K-2}(1-\epsilon_2^*)(2-\epsilon_2^*) * \left[(1-p_0)^2 - \sum_{i=1}^{N} p_i^2\right]. \end{aligned} \quad (17)$$

T_2 is a convex function of $\{-p_i\}_{i>0}$ [31] when p_0 is given. System throughput T_{app} can be expressed as

$$\begin{aligned} T_{\text{app}} &= Kp_0^{K-1}\sum_{i=1}^{N}\left(1-\epsilon_1^{0,i}\right)p_i + \binom{K}{2} p_0^{K-2}(1-\epsilon_2^*)(2-\epsilon_2^*) \\ &\quad * \left[(1-p_0)^2 - \sum_{i=1}^{N} p_i^2\right] \\ &= Kp_0^{K-1}(1-p_0) + \binom{K}{2}(1-\epsilon_2^*)(2-\epsilon_2^*)p_0^{K-2}(1-p_0)^2 \\ &\quad - Kp_0^{K-2}\left[p_0\sum_{i=1}^{N} p_i\epsilon_1^{0,i} + \frac{K-1}{2}(1-\epsilon_2^*)(2-\epsilon_2^*)\sum_{i=1}^{N} p_i^2\right] \end{aligned} \quad (18)$$

For $N=2$, $\{\epsilon_2^{j,k}\}_{k>j\geq 0} = \{\epsilon_2^{j,k}\}_{k=j+1}$ and it can be verified that the $T_{\text{app}} = T$.

For a given p_0, the problem that maximizing system throughput T_{app} is equivalent to minimizing Equation (19) as

$$\begin{aligned} \min_{\{p_i\}} \quad & p_0\sum_{i=1}^{N} p_i\epsilon_1^{0,i} + C\sum_{i=1}^{N} p_i^2 \\ \text{s.t.} \quad & \sum_{i=1}^{N} p_i = 1 - p_0 \\ & \sum_{i=1}^{N} p_i E_i \leq \bar{e} \\ & \sum_{i=1}^{N} p_i \leq 1 \\ & 0 \leq p_i \leq 1, \end{aligned} \quad (19)$$

with

$$\begin{cases} C = \dfrac{K-1}{2}(1-\epsilon_2^*)(2-\epsilon_2^*), \\ i = 1, 2, \cdots, N, \end{cases} \quad (20)$$

which is a convex problem [31] and can be solved by the convex tool in MATLAB. In Equation (19), $\bar{e}$ is the average transmission power constraint of each device. To obtain the global optimal probability distribution **P**, we get the optimal p_0 by a full search.

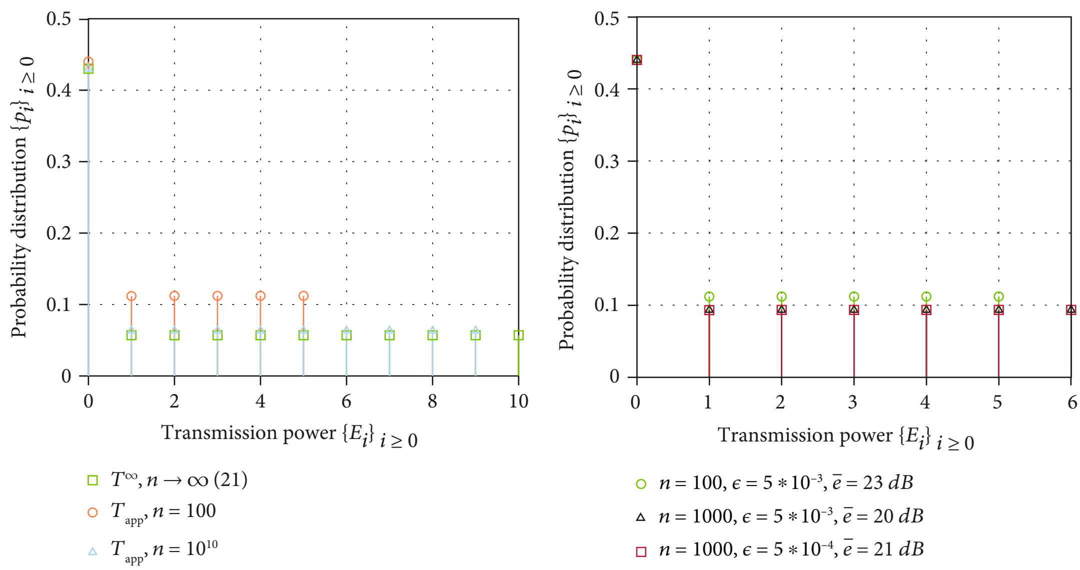
According to the optimization method above, we observe that optimal probability distribution $\{p_i\}_{i>0}$ is the same under the higher average transmission power constraint $\bar{e}$ (i.e., the higher average transmission power of devices) for finite blocklength transmission as well as infinite blocklength transmission [25] from Figure 4(a) with maximum transmission power $E_{\max} \leq 10$ dB. Moreover, it can be seen that the probability distribution of finite blocklength approaches the probability distribution of infinite blocklength transmission [25] when blocklength of packets is $n = 10^6$.

Thus, for the special case that average power constraint $\bar{e}$ is higher, system throughput T can be simplified as

$$\begin{aligned} T_{\bar{e}} &= Kp_0^{K-1}\sum_{i=1}^{N}\left(1-\epsilon_1^{0,i}\right)p_i + \binom{K}{2}p_0^{K-2} \\ &\quad * 2\sum_{j=1}^{N-1}\sum_{k=j+1}^{N} p_j p_k\left(1-\epsilon_2^{j,k}\right)\left(2-\epsilon_2^{0,j}\right) \\ &= \frac{1}{N}Kp_0^{K-1}(1-p_0)\sum_{i=1}^{N}\left(1-\epsilon_1^{0,i}\right) + \frac{1}{N^2}K(K-1)p_0^{K-2} \\ &\quad * (1-p_0)^2\sum_{j=1}^{N-1}\sum_{k=j+1}^{N}\left(1-\epsilon_2^{j,k}\right)\left(2-\epsilon_2^{0,j}\right), \end{aligned} \quad (21)$$

with $p_{i(>0)} = (1-p_0)/N$.

The optimal probability distribution $\{p_i\}$ for maximizing system throughput can be obtained by taking the derivative of $T_{\bar{e}}$ with respect to p_0. The method can be also applied to obtain optimal probability distribution of infinite



(a) $R = 1, \epsilon = 5 * 10^{-3}, E_{max} \leq 10$ dB, $\bar{e} = 7$ dB

(b) $R = 1.5, E_{max} \leq 25$ dB

FIGURE 4: Probability distribution for $N_0 = 0$ dB, $K = 3$.

blocklength transmission [25] when $\bar{e}$ is higher. However, it is a regret that there is no specific scope for a higher average transmission power. Because average transmission power is related with noise power and transmission power profiles, which depend on SINR threshold. According to the SINR threshold γ^* in Equations (7) and (8), we can see that transmission power profiles are related with blocklength n, coding rate R, and system tolerated packet error probability. Thus, the specific scope of higher average transmission power depends on blocklength n, coding rate R, and system tolerated packet error probability and noise power. In Figure 4(b), we present some specific average transmission power of different cases, under which the probability distribution for transmission power profiles is equiprobable except p_0. It can be seen from Figure 4(b) that for$n = 100, R = 1.5, \epsilon = 5 * 10^{-3}$, $\{p_i\}_{i>0}$ is equiprobable when $\bar{e} = 20$ dB, which means that average transmission power $\bar{e} = 20$ dB is higher. For $n = 1000, R = 1.5, \epsilon = 5 * 10^{-3}, \bar{e} = 23$ dB is a higher average transmission power.

4. Numerical Results

In this section, we first present numerical results of system throughput optimization method in Subsection 3.1 and analyse the factors which influence system performance for finite blocklength transmission. Then, we contrast the numerical results of finite blocklength transmission with different power control scheme, which demonstrates the merits of the proposed SIC scheme support and throughput optimization method.

4.1. Finite Blocklength Transmission Analysis. We restrict the maximum transmission power $E_{max} \leq 15$ dB. Figure 5 presents numerical results of finite blocklength transmission for average transmission power constraint$\bar{e} = 1$ dB/K, in which graphical representation $\mathbf{E}^{\infty}, n = \infty, \epsilon = 0$ denotes

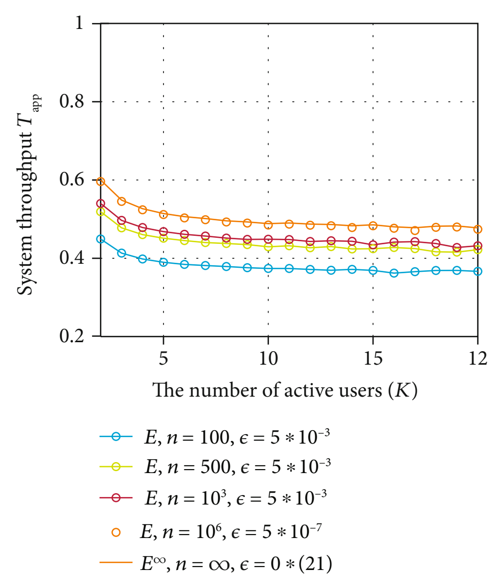


FIGURE 5: System performance of finite and infinite blocklength transmission [25] for $R = 1, N_0 = 1$ dB, $\bar{e} = 1$ dB/K.

that optimal system throughput T^{∞} of infinite blocklength transmission in [25], which can be regarded as the upper bound of finite blocklength transmission. For an expected PEP ϵ, system throughput of finite blocklength transmission will increase with n increasing as Figure 5 shows. When blocklength and PEP $n \longrightarrow \infty, \epsilon \longrightarrow 0$ for finite blocklength transmission, system throughput will approach infinite blocklength transmission system throughput T^{∞} [25]. In Figure 5, we can see $T_{app} \longrightarrow T^{\infty}$ when $n = 10^6, \epsilon = 5 * 10^{-7}$ for finite blocklength transmission.

When average transmission power of each device is higher (i.e., $\bar{e}$ is higher), optimal system throughput can be obtained by Equation (21) in Section 3.2, which can reduce

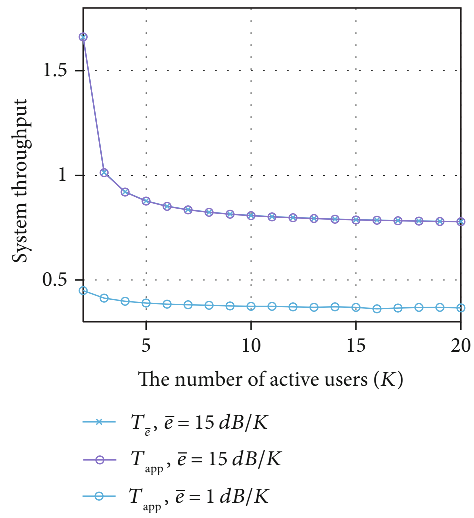


Figure 6: System performance of finite blocklength transmission for $R = 1, N_0 = 1$ dB,$n = 100$, $\epsilon = 5 * 10^{-3}$.

complexity of optimizing system throughput. As Figure 6 shows, optimal system throughput $T_{\bar{e}}$ by Equation (21) is consistent with T_{app} by convex optimization method for a higher $\bar{e}$ such as $\bar{e} = 15$ dB/K, which verifies conclusion in Section 3 that the optimal transmission power probability distribution is equal probability distribution for higher average transmission power cases. Hence, we can achieve optimal system throughput by taking the derivative of $T_{\bar{e}}$ with respect to p_0 for higher average transmission power of each device. It can also be seen from Figure 6 that system throughput can be improved by increasing average transmission power of each device.

4.2. Finite Blocklength Transmission with Different Power Control Schemes. In this subsection, we compare the proposed power control scheme with other power control schemes to validate that the proposed power control scheme can obtain superior system performance for finite blocklength transmission. For a fair comparison, we use the same average constraint of each device for all the power control schemes. We give the compared power control schemes from the following two aspects:

4.2.1. With $\mathbf{E}^{\infty}$ *[25] and*$\mathbf{P}$. Finite blocklength transmission with the transmission power profile $\mathbf{E}^{\infty}$ proposed in [25] and the optimal probability distribution $\mathbf{P}$ by Equation (19).

Transmission power distributions of $\mathbf{E}$ and $\mathbf{E}^{\infty}$ are presented in Figure 7, in which $\mathbf{E}^{\infty}$ is the transmission power profile proposed in [25] for infinite blocklength transmission with the assumption that $n = \infty, \epsilon = 0$. From Equation (7) and (8), it can be derived that the more blocklength of short packets is, the higher PEP/CPEP is under the same transmission power. Hence, within the same system tolerate PEP, shorter blocklength will need lager transmission power as Figure 7 shows. Moreover, it can be seen that transmission power of finite blocklength approaches the transmission power of infinite blocklength transmission when $n = 10^6$, $\epsilon = 5 * 10^{-7}$, which can verify the derived SINR threshold in

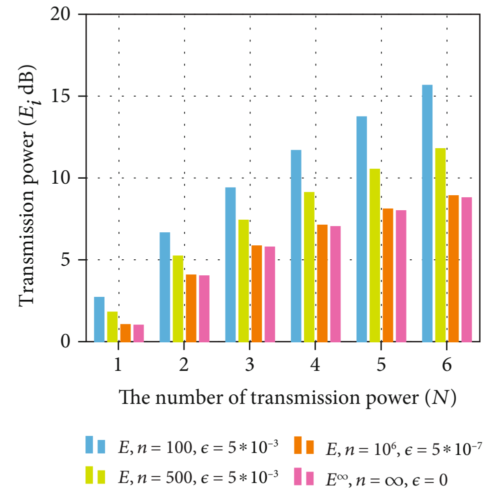


Figure 7: Transmission power distribution of finite blocklength transmission with $\mathbf{E}$ and $\mathbf{E}^{\infty}$ [25] for $R = 1, N_0 = 1$ dB .

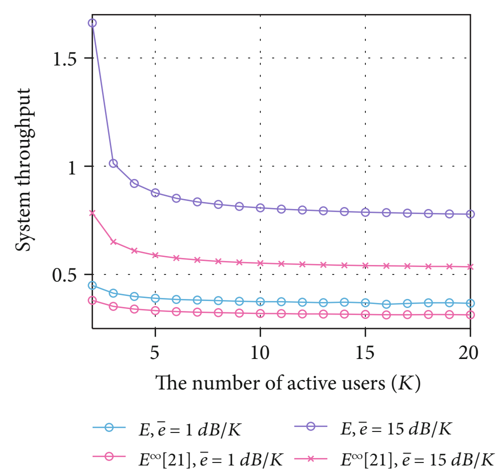


Figure 8: Transmission power distribution of finite blocklength transmission with $\mathbf{E}$ and $\mathbf{E}^{\infty}$ [25] for $R = 1, N_0 = 1$ dB, $n = 100$, $\epsilon = 5 * 10^{-3}$.

Section 2. Further, if shorter packets, such as $n = 100$, are transmitted with the infinite blocklength transmission power, PEP will be lager and will lead to system decline as Figure 8 shows. Thus, compared with infinite blocklength transmission with $\mathbf{E}^{\infty}$, system throughput will decrease in Figure 8 if short packet transmission is still with transmission power profile$\mathbf{E}^{\infty}$.

To improve system throughput for finite blocklength transmission, one way is to increase transmission power for finite blocklength transmission as Figure 7 shows. With the designed transmission power profile $\mathbf{E}$ for finite blocklength transmission in Section 2, PEP/CPEP can be controlled within an expected ϵ, which can effectively improve system throughput. It can be seen that the proposed power control scheme (with $\mathbf{E}$ and$\mathbf{P}$) can obtain superior system throughput when compared to the power control scheme with $\mathbf{E}^{\infty}$ and $\mathbf{P}$ as Figure 8 shows.

For average transmission power constraint $\bar{e} = 1$ dB/K, a system throughput gain of approximate 17% can be obtained

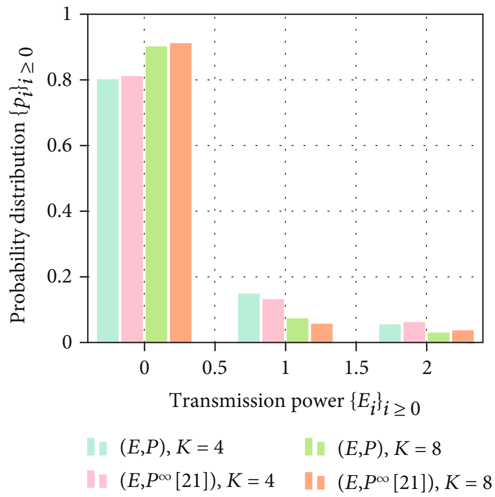


Figure 9: Probability distribution of E for finite blocklength transmission for Figure 10.

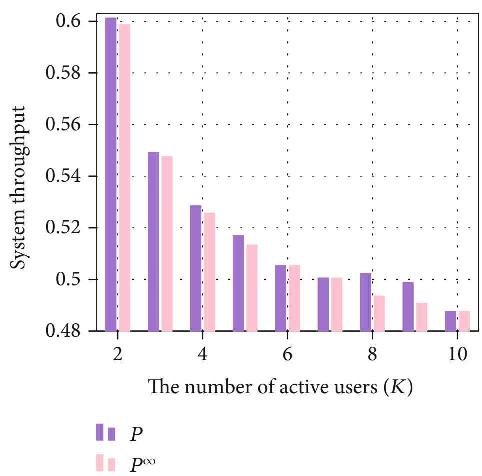


Figure 10: System performance of finite blocklength transmission with the proposed P and P^{∞} in [25] for $R = 1, n = 100, \epsilon = 5 * 10^{-3}, N_0 = 1$ dB.

at $K = 20$ in Figure 8. When transmission power constraint is higher such as $\bar{e} = 15\,\mathrm{dB}/K$, more system throughput gain can be observed. For example, a system throughput gain of approximate 45% at $K = 20$ is achieved as Figure 8 shows.

4.2.2. With $\mathbf{E}$ *and* $\mathbf{P}^{\infty}$. Finite blocklength transmission with the proposed transmission power profile $\mathbf{E}$ in this paper and the optimal probability distribution $\mathbf{P}^{\infty}$ in [25].

From Figure 8, we can see that the designed transmission power profile $\mathbf{E}$ in Section 2 plays an essential role in improving system throughput of finite blocklength transmission. In this part, we analyse system performance of finite blocklength transmission with the proposed transmission power profile $\mathbf{E}$ but with probability distribution $\mathbf{P}^{\infty}$ in [25] to observe the impact of optimal probability distribution $\mathbf{P}$ of transmission power proposed in this paper.

For a fair comparison, we use$\bar{e} = E \cdot P^{\infty}/K$ as average transmission power constrict of each device to obtain system performance of finite blocklength transmission with the proposed transmission power control scheme (with E and P). Contrast for probability distributions P and P^{∞} is presented at $K = 4$, 8 in Figure 9, from which we can see that there is tiny difference between P and P^{∞}. However, the tiny difference can bring gain on system throughput, which we can see from Figure 10. For example, a system throughput gain of approximate 1.8% can be achieved when the number of devices is $K = 8$.

5. Conclusion

In this paper, we explore decentralized power control scheme, which can support intraslot SIC decoding at receivers, to recover multiple short packets for an ALOHA-type random multiple access system. Inspired with the minimum transmission power profile design in [25], we derived the closed-form expression of short packet transmission SINR threshold and the decentralized transmission power profile, which can support intraslot SIC to recover multiple short packets in a collided slot. Further, we maximize system throughput for short packet transmission by optimizing probability distribution of proposed decentralized transmission power profile. The numerical results demonstrate that the proposed decentralized transmission power scheme and optimal probability distribution of decentralized transmission power profile for short packet transmission can improve system capacity of short packet transmission. How to design the optimal transmission power profiles which can support more than type-2 collision decoding based on SIC at receiver and decentralized power control scheme of multiple short packet recovery in the efficiency irregular repetition slotted ALOHA system will be the work we will investigate in the future.

Data Availability

Data is not applicable.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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