An Enhanced Random Access With Distributed Pilot Orthogonalization for Cellular IoT Networks

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***Abstract*—In this paper, we propose an enhanced random access (RA) with a distributed pilot orthogonalization (ERA-DPO) for mitigating packet collisions in Step3 during the RA procedure in cellular internet-of-things (IoT) networks. Even though each IoT device experiences a preamble collision in Step1, it can avoid the packet collision in Step3 by differentiating uplink pilot with the proposed technique, which provides an opportunity for the collided packets to be separated in spatial domain by multiple receive antennas. We also mathematically analyze the performance of the proposed scheme in terms of packet collision probability, throughput, and resource efficiency, based on a Markov chain model. Simulation results reveal that the proposed scheme significantly reduces the packet collision probability and increases resource efficiency compared to the conventional scheme.**

***Index Terms*—5G, cellular networks, internet-of-things (IoT), random access, distributed pilot orthogonalization.**

I. INTRODUCTION

MOST of internet-of-things (IoT) devices stay out of connections for saving energy consumptions, so they should trigger a random access (RA) procedure to establish connections with the base station (BS) when a new packet is generated. The RA procedure consists of 4-steps of handshaking [1], and it is well known that packet collisions during the transmission of Step3 message (e.g., connection or scheduling request) are directly coupled with preamble collisions in Step1 [2]. Since alleviating preamble collisions is one of straightforward solutions to reduce packet collisions, enormous efforts in both academia and industry are devoted to addressing the preamble collision problem [3]–[8].

A representative approach to mitigate preamble collisions is to reduce traffic load, so various access control mechanisms were proposed [3]–[5]. Increasing the amount of contention resources, i.e., preambles, can be another approach to achieve the same objective. Several solutions were proposed to increase the amount of available preambles based on the excellent correlation properties of the Zadoff-Chu (ZC) sequence, used as a base sequence for generating preamble signals [6]–[8].

Motivated from the use of ZC sequences, we pay attention to the demodulation reference signal (DMRS) which is a pilot signal used for coherent decoding in cellular networks such as 5G new radio (NR) [9] as well as LTE/LTE-A [10], where the ZC sequence is also used as a base sequence for generating multiple orthogonal pilot signals [11]. When each IoT device is connected with a BS after the completion of the RA procedure, the BS can assign a different orthogonal pilot signal to each of IoT devices sharing the same radio resources. Due to the centralized pilot allocation, the BS can separate the received packets in spatial domain using a multiple-input multiple-output (MIMO) detection technique without any pilot contaminations[1] [11].

While the contention is not fully resolved, i.e., during the RA procedure, the BS cannot send response to each of IoT devices in a device-specific manner. Thus, the situation that multiple IoT devices use the same uplink radio resource including pilot signal occurs when they transmit Step3 message due to the preamble collision in Step1. It is worth noting that an unresolvable packet collision occurs when the BS cannot differentiate the uplink pilot signals, i.e., pilot contamination occurs. If any mechanism that makes each of IoT devices utilize different uplink pilot in a distributed manner exists, the collided packets, i.e., Step3 messages, due to the preamble collisions may be successfully separated in spatial domain.

This paper proposes an enhanced random access with a distributed pilot orthogonalization (ERA-DPO). Due to the DPO technique, the BS may be able to separate the collided packets, i.e., Step3 messages, in spatial domain by multiple receive antennas. Based on a Markov chain model, we mathematically analyze the proposed scheme in terms of packet collision probability, throughput, and resource efficiency. Finally, we validate our analytical framework through extensive simulations. Without significant modifications, our proposed scheme can effectively accommodate more IoT devices while providing low packet collision probability and high resource efficiency.

The rest of this paper is organized as follows. In Section II, we describe the system model. In Section III, we propose an enhanced random access with a distributed pilot orthogonalization (ERA-DPO) scheme. In Section IV, we mathematically analyze our proposed scheme. In Section V, we provide numerical results. Finally, we draw conclusions in Section VI.

II. SYSTEM MODEL

We consider an orthogonal frequency division multiple access (OFDMA) based single cell network, where the BS is equipped with J antennas and N IoT devices with a single antenna are uniformly deployed within a cell coverage. Each IoT device attempts its RA when it has a new packet, where the packet arrival follows a Poisson process with an arrival rate of λ. Physical RA channel (PRACH) is periodically configured, where T_{P} denotes the period. Zadoff-Chu (ZC) sequence is used as base sequence for generating both preambles and pilot signals [11]. Preambles are used in Step1 and let N_{P} denote the number of available preambles. Furthermore, pilot signals are used in Step3 and let N_{R} denote the number of available uplink orthogonal pilot signals, i.e., DMRSs.[2] It is worth noting that an uplink pilot signal

Manuscript received April 10, 2019; revised June 30, 2019 and August 21, 2019; accepted October 23, 2019. Date of publication November 1, 2019; date of current version January 15, 2020. This work was supported by the NRF through the Basic Science Research Program funded by the Ministry of Science and ICT under Grant NRF-2019R1A2B5B01070697. The review of this article was coordinated by Dr. Z. Cai. *(Corresponding author: Bang Chul Jung.)*

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Digital Object Identifier 10.1109/TVT.2019.2950993

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[1] Pilot contamination is a phenomenon that the desired pilot signal is interfered by other signals. In this case, the BS cannot acquire correct channel state information from the corresponding pilot signal, which consequently results in a packet decoding failure.

[2] N_{R} should be carefully determined, i.e., $N_{\mathrm{R}} \leq \lfloor T_{\mathrm{sym}}/T_{\mathrm{cs}} \rfloor$, where T_{sym} and T_{cs} denote the pilot symbol duration and the time duration corresponding to the size of cyclic shift [10], respectively. T_{cs} should be larger than the maximum delay spread and thus N_{R} is not controllable and determined by the given channel propagation condition.

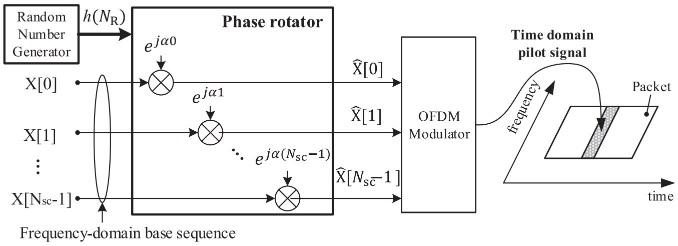

Fig. 1. Implementation of the distributed pilot orthogonalization technique.

is time-multiplexed in each of packets, i.e., Step3 messages, occupying the same bandwidth as its packet transmissions as shown in Fig. 1.

For packet decoding, the BS acquires uplink channel estimates through the received pilot signals, and attempts to decode the received packets via a zero-forcing (ZF) receiver. In our system model, we assume the perfect physical-layer phenomena during the preamble detection to clearly shed light on the collision performance, thus we do not consider erroneous- and mis-detections of preambles.

III. AN ENHANCED RANDOM ACCESS WITH DISTRIBUTED PILOT ORTHOGONALIZATION

In this section, we first propose a distributed pilot orthogonalization (DPO) technique. Thereafter, we newly propose an enhanced random access (ERA) with the DPO technique and describe the overall procedure of the proposed scheme in more detail.

A. *Distributed Pilot Orthogonalization Technique*

In the conventional IoT systems such as 3GPP LTE, when two or more IoT devices select an identical preamble (in Step1) and they accordingly receive the same response (in Step2), they simultaneously transmit their packets with the same pilot signal through the same uplink resource (in Step3). This is because the packets are transmitted before the contention is fully resolved and thus the BS could not assign a device-specific orthogonal pilot signal to each of IoT devices. To make each of IoT devices utilize a different orthogonal pilot signal, we propose a distributed pilot orthogonalization (DPO) technique, where each IoT device randomly selects a pilot signal among a set of orthogonal pilot signals during the packet transmissions. This simple but powerful technique can provide the ability of packet collision resolution to the BS during the packet transmissions.

Fig. 1 describes the implementation of the proposed DPO technique. Let $X[k]$ for $k \in \mathcal{K} \triangleq \{0, \ldots, N_{\mathrm{sc}} - 1\}$ denote for ZC sequence in frequency domain. Each device selects a random integer between 1 and N_{R}, i.e., $h(N_{\mathrm{R}}) = \{x \in \mathbb{Z} : 1 \le x \le N_{\mathrm{R}}\}$. The pilot signal in frequency domain can be expressed as $\widetilde{X}[k] = X[k]e^{j\alpha k}$ for $k \in \mathcal{K}$, where $\alpha = 2\pi \cdot h(N_{\mathrm{R}})/N_{\mathrm{R}}$. With the frequency-domain pilot signal $\widetilde{X}[k]$, the time-domain pilot signal can be generated following a common OFDM symbol generation procedure, and it is time-multiplexed within each of packets. Note that the 4-th symbol duration is used to convey the time-domain pilot signal when the normal cyclic prefix is utilized in LTE/LTE systems [10].

B. *An Enhanced RA With DPO Technique*

The proposed scheme consists of 4-steps of handshaking, and the detail of each step is as follows:

- **(Step1) Preamble Transmissions**: Each IoT device randomly selects a preamble among a set of N_{P} preambles, and transmits it through a physical random access channel (PRACH).

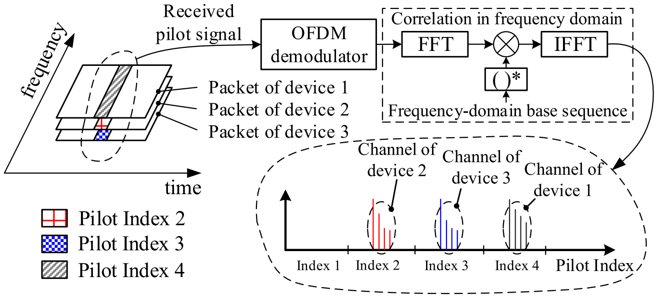

Fig. 2. Implementation of the decomposition of uplink pilot signals.

- **(Step2) Random Access Response**: The BS detects which preambles are active. Since the BS cannot recognize the actual number of transmitters and whom transmit the corresponding detected preambles, it adopts a preamble-specific response mechanism. Thus, the BS transmits an RA response (RAR) for each detected preamble, which contains an RA preamble identifier (RAPID) and uplink grant (UG). Each IoT device finds the adequate RAR by comparing the RAPID value contained in RAR with its preamble index used in Step1. If multiple IoT devices select the same preamble in Step1, i.e., preamble collision, they consequently use the same radio resource indicated by the UG value contained in RAR when they transmit packet in the subsequent step.
- **(Step3) Distributed Pilot Orthogonalization and Packet Transmissions**: Each IoT device randomly selects an uplink pilot signal among N_{R} orthogonal pilot signals and multiplexes it into the packet. The packet is transmitted through the assigned radio resource indicated by the UG value in RAR received in Step2.
- **(Step4) Pilot Decomposition, Data Decoding, and Acknowledgement**: To acquire uplink channel estimates, the BS calculates correlation between the received pilot signals and the base sequence as shown in Fig. 2. Multiple channel impulse responses (CIRs) up to N_{R} can be observable from the correlation result, and they can be separable in time domain [10]. With the acquired channel estimates, the BS attempts to decode the received packets. When each of IoT devices sharing the same uplink resource utilize a different uplink pilot signal each other in Step3, the BS can successfully decode the entire packets. On the contrary, if two or more IoT devices among the entire devices sharing the same uplink resource use the same pilot signal, the BS cannot further decompose the corresponding pilot signal. Consequently, the BS fails to decode the entire packets since it cannot use a full rank ZF matrix to exploit the antenna technique. The BS transmits acknowledgement messages to the IoT devices where the packets are successfully decoded.

Fig. 2 shows the implementation of the pilot decomposition with an example that three IoT devices transmit packets through the same uplink resource. In this example, all IoT devices use different pilots so that the BS can generate a 3×3 full rank ZF matrix with the acquired channel estimates. Consequently, their collided packets can be separated in spatial domain and decoded with ZF decoding. It is worth noting that if two or more IoT devices among three IoT devices in this example utilize the same pilot signal, the BS cannot recognize the actual number of transmitters and fails to make a correct full rank ZF matrix, which leads to a decoding failure of the entire packets, i.e., unresolvable packet collision.

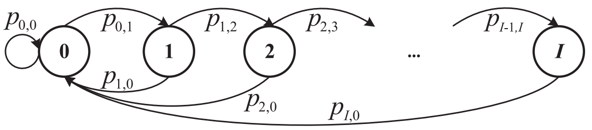

Fig. 3. A state transition diagram of the proposed Markov chain.

IV. PERFORMANCE ANALYSIS

In this section, we propose an analytical framework based on a Markov chain to mathematically analyze our proposed scheme in terms of packet collision probability, throughput, and resource efficiency. Fig. 3 shows the proposed Markov chain, where each state represents the number of RA attempts of each of IoT devices.

Let $\mathcal{S} = \{0, 1, 2, \ldots, i, \ldots, I\}$ denote the state space, where I represents the number of maximally allowed RA attempts. $\pi_i(t_n)$ represents the state probability that the number of RA attempts equals to i at time t_n, and π_i represents the corresponding steady-state probability. Thus, $\boldsymbol{\pi} = \{\pi_i\}$ for $i \in \mathcal{S}$ represents the distribution of the steady-state probabilities. A state transition occurs whenever each IoT device attempts RA, and its probability from state j to state k, $p_{j,k}$, is expressed as

$$p_{j,k} = \begin{cases} e^{-\lambda T_{\mathrm{P}}}, & j = 0, k = 0 \\ 1 - e^{-\lambda T_{\mathrm{P}}}, & j = 0, k = 1 \\ p_{\mathrm{c}}, & j = 1, \ldots, I-1, k = j+1 \\ 1 - p_{\mathrm{c}}, & j = 1, \ldots, I-1, k = 0 \\ 1, & j = I, k = 0 \\ 0, & \text{otherwise}, \end{cases} \tag{1}$$

where p_{c} represents the packet collision probability.

Packet collision occurs when two or more IoT devices selecting the same preamble in Step1 select the same uplink pilot signal in Step3. We derive p_{c} from the viewpoint of an IoT device of interest, d_o. To derive p_{c}, we should obtain the RA attempt probability of each IoT device, τ, which can be derived from a stationary distribution of the Markov chain. The steady-state probabilities can be expressed as

$$\pi_0 = \pi_0 p_{0,0} + \sum_{i=1}^{I} \pi_i p_{i,0} \tag{2}$$

and

$$\pi_i = \pi_0 \prod_{j=0}^{i-1} p_{j,j+1} \text{ for } i \in [1, I]. \tag{3}$$

By using the normalization condition for the stationary distribution, we have

$$1 = \sum_{i=0}^{I} \pi_i = \pi_0 \left(p_{0,0} + \sum_{i=1}^{I} \left((1 + p_{i,0}) \prod_{j=0}^{i-1} p_{j,j+1} \right) \right). \tag{4}$$

Therefore, by using (4), π_0 can be expressed as

$$\pi_0 = \left(p_{0,0} + \sum_{i=1}^{I} \left((1 + p_{i,0}) \prod_{j=0}^{i-1} p_{j,j+1} \right) \right)^{-1}. \tag{5}$$

Now, we have

$$\tau = 1 - \pi_0, \tag{6}$$

which is a function of p_{c} (see (1) and (5)).

When $n + 1 \leq J$,[3] the packet collision probability p_c can be expressed as

$$p_{\mathrm{c}} = 1 - \sum_{n=0}^{J-1} f\left(n, N-1, \frac{\tau}{N_{\mathrm{P}}}\right) g\left(n+1, N_{\mathrm{R}}\right), \tag{7}$$

where

$$f(n, N-1, \frac{\tau}{N_{\mathrm{P}}}) \triangleq \binom{N-1}{n} \left(\frac{\tau}{N_{\mathrm{P}}}\right)^{n} \left(1 - \frac{\tau}{N_{\mathrm{P}}}\right)^{N-1-n}, \tag{8}$$

which represents the probability that n among $N-1$ IoT devices attempt RAs with the identical preamble selected by the IoT device d_o, and

$$\begin{aligned} g\left(n+1, N_{\mathrm{R}}\right) &\triangleq \prod_{j=0}^{n} \left(\frac{N_{\mathrm{R}} - j}{N_{\mathrm{R}}}\right) \\ &= \frac{(N_{\mathrm{R}} - 1)!}{(N_{\mathrm{R}})^{n} \left(N_{\mathrm{R}} - (n+1)\right)!}, \end{aligned} \tag{9}$$

which represents the probability that $n+1$ IoT devices select different pilots with each other.

Otherwise, when $n + 1 > J$, $p_{\mathrm{c}} = 1$, since the BS cannot support more than J data streams due to the physical limitation of the antenna technique regardless of the occurrence of pilot contaminations. It is worth noting that the packet collision probability is reduced due to (9), which corresponds to the effect of the DPO technique. Finally, (6) and (7) comprise a non-linear system and thus τ and p_{c} can be found by numerical methods.

Throughput, η, is defined as the number of IoT devices which succeed in their RAs without packet collision. When the effective load per RA slot is given by

$$\tilde{n} \triangleq \sum_{n=0}^{N} n f\left(n, N, \tau\right), \tag{10}$$

$\eta(\tilde{n})$ can be calculated as

$$\begin{aligned} \eta(\tilde{n}) &= \tilde{n} \times p_{\mathrm{s}}(\tilde{n}) \\ &= \tilde{n} \sum_{j=0}^{\tilde{n}-1} f\left(j, \tilde{n}-1, \frac{1}{N_{\mathrm{P}}}\right) g\left(j+1, N_{\mathrm{R}}\right), \end{aligned} \tag{11}$$

where $p_{\mathrm{s}}(\tilde{n})$ represents the success probability when $\tilde{n}$ IoT devices are contending at a single RA slot. It is noteworthy that as $\tilde{n}$ increases the success probability decreases because the contention becomes severer. Accordingly, there exists $\tilde{n}^{\star}$ to maximize throughput, which can be found by solving the first derivative of $\eta(\tilde{n})$, i.e., $\frac{d\eta(\tilde{n})}{d\tilde{n}} = 0$.

Resource efficiency, ζ, is defined as the ratio of the number of RA-success IoT devices to the amount of assigned uplink radio resources, which quantifies how much the radio resources are efficiently utilized without waste. Considering the effective load $\tilde{n}$,

$$\zeta(\tilde{n}) = \frac{\eta(\tilde{n})}{N_{\mathrm{P}} \left(1 - \left(1 - \frac{1}{N_{\mathrm{P}}}\right)^{\tilde{n}}\right)}, \tag{12}$$

where the denominator represents the amount of allocated resources, which is related to the number of detected preambles.

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[3] n represents the number of IoT devices, which use the same uplink radio resource with the IoT device d_o. Hence, $n+1$ packets are transmitted through the corresponding resource in this case.

TABLE I
SIMULATION PARAMETERS AND VALUES [1], [11]

Parameters	Values
Number of antennas at the BS, J	$1 \sim 8$
Number of IoT devices, N	$10,000 \sim 50,000$
RA arrival rate, λ	$1/300$ (s^{-1})
PRACH period, T_{P}	10 (ms)
Maximum number of RA trials, I	10
Number of available preambles, N_{P}	8 [7]
Number of uplink pilots, N_{R}	$1 \sim 6$ [10]

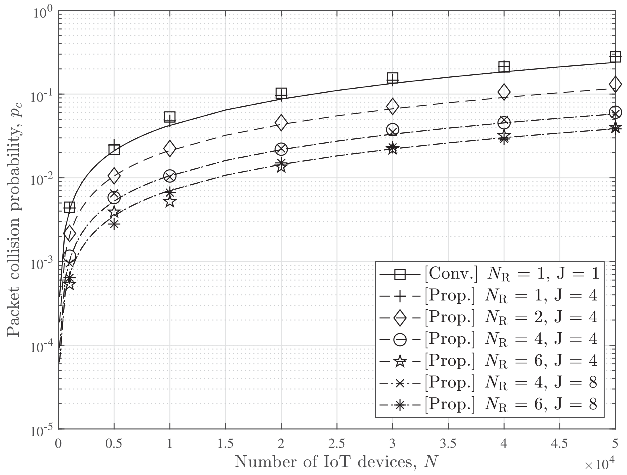

Fig. 4. Packet collision probability for varying the number of IoT devices.

V. NUMERICAL RESULTS

In order to validate our analytical framework, we perform system-level simulations using a process-oriented discrete-event simulation package, CSIM, with the following parameters listed in Table I. In all figures, lines and markers represent the analysis and the simulation results, respectively. For a fair comparison, the conventional RA scheme is used as a baseline scheme.

Fig. 4 shows the packet collision probability for varying the number of IoT devices, N, according to the various combination of N_{R} and J when $\lambda = 1/300(s^{-1})$ and $N_{\mathrm{P}} = 8$. From the observations, we verify that the proposed scheme can effectively enhance the performance of the conventional one. When the BS is equipped with multiple antennas, the packet collision probability can be significantly reduced. Even though the proposed DPO technique is applied, any promising gain cannot be achievable when the BS is equipped with a single antenna. It is shown that increasing N_{R} rather than J is much effective to improve the performance. However, since N_{R} is a given parameter according to the channel condition, letting the BS be equipped with more antennas can be the best strategy.

Fig. 5 shows the throughput for varying the effective load per RA slot, $\tilde{n}$, according to the various combination of N_{R} and J when $\lambda = 1/300(s^{-1})$ and $N_{\mathrm{P}} = 8$. When $\tilde{n}$ is small, the number of RA-success IoT devices linearly increases according to $\tilde{n}$, which leads to an increase in throughput. Beyond a certain point, however, the throughput decreases since the packet collisions become severer as $\tilde{n}$ increases. It is shown that the proposed ERA-DPO can successfully support much more traffic load compared to the conventional one.

Fig. 6 shows the resource efficiency for varying $\tilde{n}$ according to the various combination of N_{R} and J when $\lambda = 1/300(s^{-1})$ and $N_{\mathrm{P}} = 8$. The conventional RA scheme shows a gradual decrease in resource efficiency as $\tilde{n}$ increases, since the allocated resources are wasted due to the severe packet collisions. On the contrary, the proposed scheme shows relatively high resource efficiency since the packet collisions in Step3 can be effectively reduced through the proposed DPO technique even though the allocated resources are unintentionally shared by multiple IoT devices due to the preamble collisions in Step1. This implies that the corresponding resource is reused by multiple IoT devices and thus the resource efficiency can be more than 1. Note that $N_{\mathrm{R}} \geq 4$ is sufficient enough to achieve considerable improvement of the resource efficiency.

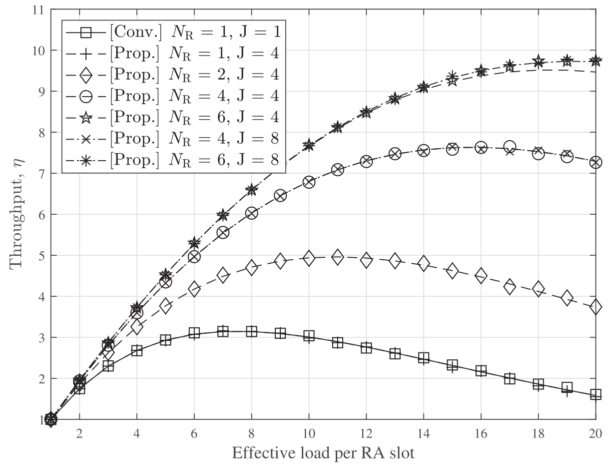

Fig. 5. Throughput for varying the effective load per RA slot.

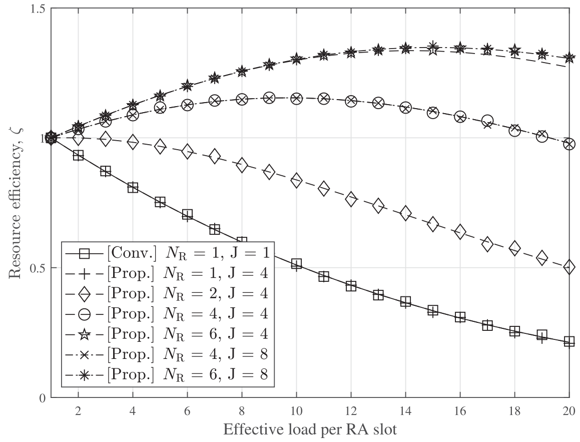

Fig. 6. Resource efficiency for varying the effective load per RA slot.

VI. CONCLUSION

In this paper, we proposed an enhanced random access with a distributed pilot orthogonalization (ERA-DPO) for cellular IoT networks. Our proposed scheme can reduce the packet collisions in Step3 even though multiple devices experience preamble collisions in Step1. We mathematically analyzed our proposed scheme based on a Markov chain model in terms of packet collision probability, throughput, and resource efficiency. Simulation results revealed that our proposed scheme can provide much lower packet collision probabilities and higher resource efficiency compared to the conventional one. Our proposed scheme can be compatible with the systems which use ZC sequence as a base sequence for uplink pilot signals such as 5G NR as well as LTE/LTE-A.

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