IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received July 12, 2021, accepted August 3, 2021, date of publication August 6, 2021, date of current version August 16, 2021.

Digital Object Identifier 10.1109/ACCESS.2021.3103123

Access Priority Provisioning Based on Random Access Parallelization for Prioritized Cellular IoT

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This work was supported in part by the National Research Foundation of Korea (NRF) Grant through Korea Government (MSIT) under Grant 2020R1G1A1101176, and in part by the National Research Foundation of Korea (NRF) Grant through Korea Government (MSIT) under Grant 2020R1F1A1069934.

ABSTRACT In order to support diverse access requirements from various internet-of-things (IoT) applications, we propose a novel access priority provisioning technique that can be applied to the random access (RA) procedure in cellular networks. A key feature of our proposed technique is to allow for each IoT device to differentiate the number of simultaneously transmitted preambles during the RA procedure according to its own access priority. Since simultaneous transmission of multiple preambles (i.e., RA parallelization) can achieve the diversity effect during the access phase (i.e., RA procedure), the IoT devices using more preambles can achieve better access performance compared to those using fewer preambles. This motivates us to newly propose our access priority provisioning technique. We mathematically analyze our proposed technique in terms of the RA failure probability and validate our analytical framework with extensive computer simulations. From the results, we verify the feasibility of our proposed technique for supporting diverse access priorities during the access phase (i.e., RA procedure) without significant modifications to the conventional one.

INDEX TERMS Cellular networks, Internet-of-Things, random access, access priority, multi-preamble.

I. INTRODUCTION

Evolution of wireless communication technologies toward the fifth-generation (5G) enables everything to be connected through the internet. For example, lots of information related to human activities have been recorded, monitored through various types of IoT applications (e.g., health monitoring, smart home, intelligent transportation, industrial automation), and exchanged through cellular networks [1]. However, unfortunately, conventional cellular networks have not been designed to accommodate such diverse IoT applications. Accordingly, enormous efforts have been made in both academia and industry to support the emerging IoT scenario in cellular networks, which is referred to massive machine-type communications (mMTC) or massive IoT (mIoT) as one of the main use cases of 5G [2].

The associate editor coordinating the review of this manuscript and approving it for publication was Fan-Hsun Tseng.

In cellular networks, an extremely large number of IoT devices are expected to be deployed, where the number of connected devices will reach 500 billion by 2030 [3]. Each IoT device sporadically generates small-sized packets to report sensing information to the IoT server through a base station (BS). In particular, an IoT device stays out-of-connection with the BS to reduce energy consumption due to the sporadic packet generation. This implies that each of IoT devices should perform random access (RA) procedure to establish a connection with the BS, whenever transmitting data packets to the IoT server. The RA procedure adopted in the existing cellular systems such as LTE/LTE-A/5G consists of four-steps of handshaking procedure [4], [5]. Due to the densely deployed IoT devices in cellular IoT networks, simultaneous RA attempts at a certain RA slot (or, equivalently, physical RA channel (PRACH)) may cause collision problem. Collision problem highly causes the poor access performance (i.e., RA failure) at the device side. To be specific, IoT devices may spend considerable time to access the networks and thus the networks cannot guarantee acceptable end-to-end delay according to their access priority.

To tackle the collision problem, a number of studies have been actively performed for several years. Various access class barring (ACB) mechanisms have been proposed to dynamically regulate control parameters to cope with the collision issue during the RA procedure [6], [7]. Ko *et al.* efficiently utilized the fixed timing alignment (TA) information value of stationary IoT devices during the RA procedure to mitigate the collisions [8]. Wang and Wong took the advantages of both ACB and TA information to reduce the collision probability [9]. In addition to utilizing ACB and TA information, increasing the amount of available contending resources (e.g., RA preambles) can be useful to mitigate the collisions [10].

Previous studies [6]–[10] have mainly focused on mitigating the occurrence of collisions while not considering the notion of *access priority* or quaility-of-service (QoS) during the access phase. Due to the diverse applications (e.g., smart city, smart factory, etc.) supported by the IoT networks, new solutions should support the diverse access requirements from the access phase. To support multiple access priorities, Rivero-Angeles *et al.* [11] investigated a prioritization mechanism based on adjustment of retransmission probability, which has the similar effect to adjust the back-off window size according the priority level, discussed in [12]. Separation of the contention resources (i.e., RA preambles) into multiple non-overlapping groups has traditionally considered in various studies [2], [13], and [14]. Since resource separation approach may cause resource inefficiency [15], power-domain prioritization strategies were introduced [15]–[17]. However, the performance of such approach may also highly depend on the wireless channel conditions which may not be adequate to provide reliable communication services.

In this paper, we propose a novel access priority provisioning technique to support diverse access priorities in prioritized cellular IoT networks. Our proposed technique enables each IoT device to simultaneously transmit multiple preambles and differentiate the number of simultaneously transmitted preambles according to its access priority. Since simultaneous transmission of multiple preambles (i.e., RA parallelization) can achieve the diversity effect during the access phase, the IoT devices using more preambles can achieve better access performance compared to the other devices using fewer preambles. We mathematically analyze our proposed technique in terms of RA failure probability. Through extensive computer simulations, we validate our analytical framework and verify that our proposed technique can provide better access performance to the devices with higher priority than other devices with lower priority. Without significant modifications to both specifications or implementations in practice, we verify the feasibility of our proposed technique for supporting access priority during the access phase, i.e., RA procedure.

The rest of this paper is organized as follows. In Section II, we provide background on the traditional RA procedure. In Section III, we describe our system model. In Section IV, we newly propose an access priority provisioning technique. In Section V, we mathematically analyze our proposed technique and verify its validity through extensive computer simulations in Section VI. Finally, we draw conclusions in Section VII.

II. BACKGROUND: RANDOM ACCESS PROCEDURE IN CELLULAR NETWORKS

In cellular systems, a connection between each IoT device and the BS is pre-required for data communications. For establishing a connection, a device should proceed 4-steps of RA procedure. We summarize the overall descriptions on the conventional RA procedure in cellular networks (e.g., LTE/LTE-A/5G) as follows [18]:

- **Step1. Preamble transmissions:** Each IoT device randomly selects a single RA preamble among a set of available RA preambles, and transmits it on the PRACH.
- **Step2. Random access responses:** The BS detects which preambles are active. In response to the detected preambles, the BS transmits random access response (RAR) messages, each of which consists of an RA preamble identifier (RAPID), a timing alignment (TA), an uplink grant (UG), and a temporary identifier. Each IoT device which transmitted a preamble at the first step waits for the RAR message containing the same RAPID. If there exists the corresponding RAR message, each device utilizes information within the message for the subsequent step (i.e., Step3).
- **Step3. Scheduled transmissions:** Each IoT device transmits its scheduled message (e.g., connection request message) on the assigned uplink resource on physical uplink shared channel (PUSCH), indicated by the UG value contained in the RAR message received in the second step. In order to determine whether the resource collision on the used uplink resource occurs or not, each IoT device starts a contention resolution (CR) timer once the Step3 message is transmitted.
- **Step4. Acknowledgement:** The BS echoes the identifiers of the IoT devices, whose transmitted scheduled messages are successfully decoded without any resource collisions. If each IoT device receives the correct acknowledgement (ACK) message before the CR timer expires, then it regards the RA attempt as a success. Otherwise, it regards the RA attempt as a failure and reattempts the RA procedure at the next-available RA slot after performing a back-off.

Fig. 1 describes the overall RA procedure, where two IoT devices attempt their RAs. Fig. 1 (a) shows an example assuming two IoT devices succeed in their RAs. On the other hand, Fig. 1 (b) shows another example that two IoT devices experience a preamble collision at Step1, which consequently results in the resource collision at Step3. To be specific, this

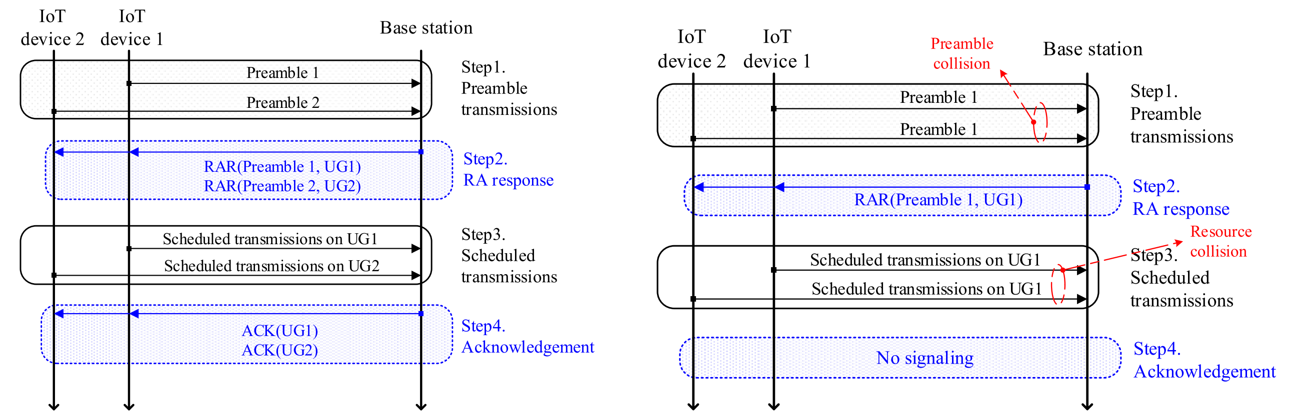


FIGURE 1. **The RA procedure: (a) an example of RA success and (b) an example of RA failure.**

is because when a certain preamble (e.g., preamble 1) is simultaneously selected by two IoT devices at Step1, both IoT devices (e.g., IoT device 1 and 2) regard the received RAR message at Step2 as their own RAR messages, and consequently attempt to send each of Step3 messages on the identical uplink resources (e.g., UG1) at Step3. In this case, the BS fails to decode the signal received through the uplink resource at Step3 due to the resource collision, and thus, it cannot echo the corresponding ACK message at Step4.

III. SYSTEM MODEL

In this section, we explain the system model and underlying assumptions considered throughout the paper. Fig. 2 describes our system model. We consider a single cell BS and a large number of IoT devices deployed within a cell coverage. An IoT device is regarded as active when it has packets to transmit in uplink direction, otherwise it is regarded as inactive [10]. For uplink transmission, each active IoT device initiates a connection with the BS by attempting the RA procedure at the next-available RA slot (or, equivalently, PRACH). PRACH is commonly periodically available. For analytical tractability, we focus on a specific single PRACH in this paper. Let n denote the number of active IoT devices ready to attempt the RA procedure.[1] We assume that each IoT device has different access priority and consider two types of access priorities for simplicity.[2] Accordingly, let n_h and n_l denote the number of IoT devices with high-priority and low-priority, respectively and $n = n_h + n_l$.

Let M denote the number of available RA preambles in the system, where M is commonly set to 64 in LTE/LTE-A/5G [18]. In the current systems, each IoT device triggers the RA procedure by transmitting *only* a single preamble, which does not embed any functionality to indicate its access priority. In our proposed technique, this constraint on the number of simultaneously transmitted preambles is relaxed, and thus, each IoT device will be allowed to simultaneously transmit multiple preambles [19]. Furthermore, we differentiate the number of simultaneously transmitted preambles according to the access priority, which will be further explained in the next section. Hence, let k_h and k_l represent the number of preambles to be simultaneously transmitted at Step1 by the devices with high-priority and low-priority, respectively, and $k_h \geq k_l$. In particular, $k_h = k_l$ in [19] and $k_h = k_l = 1$ in current LTE/LTE-A/5G systems [18].

We assume perfect physical-layer aspects, e.g., no erroneous detections and mis-detections during the preamble detection phase, and do not consider the scenario where the amount of radio resources is constrained.

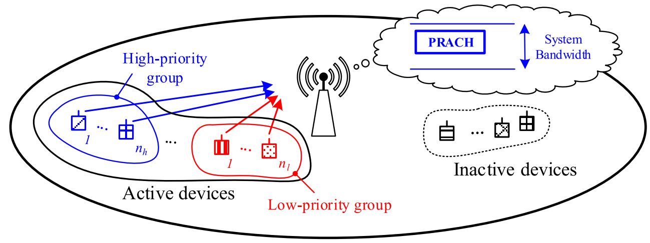


FIGURE 2. **The system model assumes a single cell BS and a large number of IoT devices categorized into two groups according to the access priority: high-priority and low-priority. Among them, active IoT devices which have packets to transmit in uplink direction attempt RA procedures.**

IV. ACCESS PRIORITY PROVISIONING TECHNIQUE

In this section, we briefly describe the concept of access priority. Then, key features of our proposed technique will be explained. Finally, the detailed explanation on the overall procedure will be followed.

A. ACCESS PRIORITY

Cellular networks have not been designed for different access requirements of diverse applications, and quality-of-service (QoS) is supported after the completion of the RA procedure in general [16] and [20]. Even though a certain IoT device

[1] Some IoT devices may be in reattempting their RAs due to the previous RA failure.

[2] Note that our proposed technique can readily support multiple access priorities, not restricted to support two access priorities only.

needs an urgent access to the networks, there do not exist any mechanisms to guarantee its access priority (e.g., emergency) during the access phase. This situation becomes severer when the number of contending devices increases. Thus, a number of studies have focused on pioneering the notion of access priority, which refers to the priority during the access phase, i.e., RA procedure [16]. Due to the emergence of various use cases in 5G, an access priority provisioning has become more important issue.

B. KEY FEATURES

Recently, an RA parallelization (RAP) technique was proposed [19], which generalizes the conventional RA procedure by relaxing the constraint on the number of simultaneously transmitted preambles at Step1 of the RA procedure.[3] We notice that the functionality of access priority can be implemented by differentiating the number of simultaneously transmitted preambles according to the access priority. Consequently, the IoT devices using more preambles can achieve better access performance compared to those using fewer preambles due to the diversity effect achieved by the simultaneous transmission of multiple preambles. It is worth noting that transmitting more preambles will be preferred to the IoT scenarios requiring higher access priorities.

C. OVERALL PROCEDURE

The proposed technique also follows four-steps of handshaking procedure. Due to the newly proposed features especially in the first step, there are some modifications in the subsequent steps. The detailed explanation on each of modified steps is as follows:

- **Step1. Priority-based multi-preamble transmissions**: Each IoT device triggers the RA procedure by simultaneously transmitting multiple preambles to the BS through the PRACH. While selecting the preambles, each IoT device differentiates the number of preambles according to its access priority. To be specific, each IoT device with high-priority (low-priority) selects different $k_h(k_l)$ preambles among the available RA preambles and transmits them at the same time to the BS via PRACH.[4]
- **Step2. Random access responses**: The BS detects active preambles and responds to those of detected preambles by sending RAR messages, each of which contains a preamble index (i.e., RAPID), a TA value, a UG, and a temporary identifier. However, since each IoT device transmits multiple preambles in the second step, it should identify multiple RAR messages according to its access priority, i.e., $k_h(k_l)$ preambles $\rightarrow$ $k_h(k_l)$ RAR messages. After identifying multiple RAR messages, it proceeds multiple subsequent steps in parallel, i.e., $k_h(k_l)$ RAR messages $\rightarrow$ $k_h(k_l)$ scheduled transmissions.[5]
- **Step3. Multiple scheduled transmissions**: This step is similar with that of the traditional RA procedure, except that each IoT device transmits multiple identical messages. To be specific, each IoT device makes multiple replicas (e.g., up to k_h and k_l for high-priority and low-priority IoT devices, respectively.) of its scheduled message (e.g., connection request). Then, it transmits each packet on each of the assigned uplink resources, which is indicated by the UG value contained in each of RAR messages received at Step2. Each IoT device triggers CR timers to determine whether the resource collisions occur or not. Note that this step achieves the diversity effect at the cost of resource efficiency caused by efforts to transmit multiple replicas of the original scheduled message.
- **Step4. Acknowledgement**: When the BS succeeds in decoding the packets received at Step3, it transmits the ACK messages to the IoT devices whose packet is successfully decoded. If each IoT device receives (more than or equal to one) ACK message, then its RA attempt is regarded as a successful completion. Otherwise, if each IoT device cannot receive any ACK messages until the CR timer expires, it should reattempt the RA procedure at the next-available RA slot after performing a back-off.

Fig. 3 depicts the effect of access priority provisioning, where IoT device 1 with high-priority and IoT device 2 with low-priority attempt their RAs with two preambles and a single preamble, respectively. In Fig. 3 (a), both IoT devices succeed in their RAs regardless of their access priorities, since no preamble collision occurs. In Fig. 3 (b), however, even though the preamble collision (i.e., preamble 2) at Step1 leads to the packet collision at Step3,[6] IoT device 1 consequently succeeds in its RA attempt due to the success of RA initiated by the preamble 1. This simple example seems to be sufficient enough to describe why multi-preamble transmission can help to provide the functionality of access priority during the access phase, i.e., RA procedure.

V. PERFORMANCE ANALYSIS

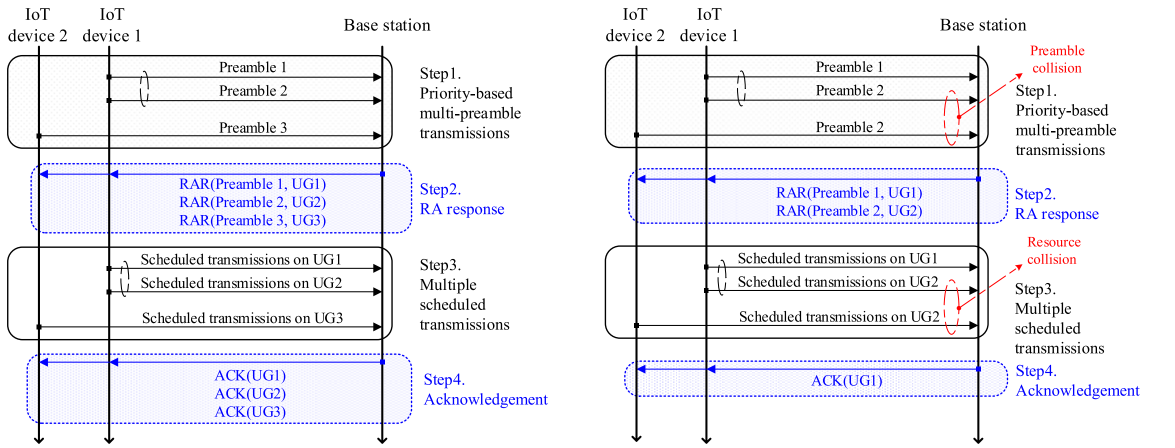
In this section, we provide an analytical framework to capture the performance of our proposed technique. We analyze our

[3]The RAP technique allows for each IoT device to transmit multiple preambles at Step1 of the RA procedure, which enables for each device to perform multiple RAs in parallel at the same time. This simple modification can significantly increase the probability that at least one RA attempt among multiple RA attempts succeeds, which is referred as *preamble diversity effect* during the access phase [19]

[4]The system can configure $k_h \geq k_l \geq 1$ in general. If $k_h = k_l$ then the system does not support the access priority, and the system operates in the same manner with the conventional one when $k_h = k_l = 1$.

[5]It is worth noting that each IoT device may expect the same number of RAR messages with that of preambles transmitted at Step1, i.e., $k_h(k_l)$ RAR messages for the IoT devices with high-priority(low-priority), are received, but some of RAR messages may be missed due to the occurrence of mis-detections during the preamble detection phase. However, since this event can be effectively avoided via open-loop power control such as power ramping, and thus, we do not consider such scenario in this paper.

[6]Since the preamble 2 is utilized by two IoT devices at the same time and the BS cannot recognize the occurrence of preamble collision during the preamble detection phase, IoT device 1 and 2 consequently send their data packets via the same uplink resource, i.e., UG 2.



(a) Two IoT devices succeed in their RAs without any preamble/resource collisions (b) Two IoT devices fail in their RAs due to preamble/resource collisions

FIGURE 3. **RA procedure with the proposed access priority provisioning technique: (a) success example and (b) failure example.**

proposed technique in terms of RA failure probability from a single PRACH perspective when the number of contending devices is given arbitrarily. Without loss of generality, we consider analysis from the perspective of a single IoT device of interest, d_o. We assume that the total number of contending IoT devices are given by $n_h + n_l$ including d_o, where n_h and n_l represent the number of IoT devices with high-priority and low-priority, respectively. The IoT device d_o may be included either n_h or n_l according to its access priority. Thus, the IoT device d_o contends with $n_h + n_l - 1$ other devices during the RA procedure.

From the viewpoint of a single IoT device, the RA failure occurs when the entire transmitted preambles are used by other devices at the same time regardless of its access priority.[7] In other words, if there exists at least one preamble exclusively utilized by d_o (equivalently, not utilized by other IoT devices), the IoT device d_o can successfully complete its RA procedure. The RA failure probability can be derived based on the well-known inclusion-exclusion principle in the field of probability theory [21].

Proposition 1 (RA Failure Probability of IoT Devices With High-Priority): For the given n_h, n_l, k_h, k_l and M, the RA failure probability of a single IoT device with high-priority, p_h, is derived as follows:

$$p_h = \sum_{m=0}^{k_h} (-1)^m \left(\frac{(M-k_h)!\,(M-m)!}{(M-m-k_h)!M!} \right)^{n_h-1} \times \left(\frac{(M-k_l)!\,(M-m)!}{(M-m-k_l)!M!} \right)^{n_l} \binom{k_h}{m}. \quad (1)$$

Proof: Let $\mathcal{A}_m$ denote an event that m preambles among k_h preambles selected by d_0 are exclusively utilized by d_0.

We define Ω_h as the entire sample space which includes all possible outcomes when each of $n_h - 1$ devices independently selects k_h preambles and each of n_l devices independently selects k_l preambles. Then, p_h is given by

$$p_h = \frac{n(\mathcal{A}_0)}{n(\Omega_h)} = 1 - \frac{n\left(\bigcup_{m=1}^{k_h} \mathcal{A}_m\right)}{n(\Omega_h)}, \quad (2)$$

where $n(\mathcal{A}_m)$ denote the number of possible outcomes when the event $\mathcal{A}_m$ is considered.

Using the inclusion-exclusion principle, the term

$$n\left(\bigcup_{m=1}^{k_h} \mathcal{A}_m\right)$$

can be obtained as follows:

$$n\left(\bigcup_{m=1}^{k_h} \mathcal{A}_m\right) = \sum_{m=1}^{k_h} \binom{M-m}{k_h}^{n_h-1} \times \binom{M-m}{k_l}^{n_l} \binom{k_h}{m} (-1)^{m-1}. \quad (3)$$

Similarly, the term $n(\Omega_h)$ can be obtained as follows:

$$n(\Omega_h) = \binom{M}{k_h}^{n_h-1} \binom{M}{k_l}^{n_l}. \quad (4)$$

By plugging (3) and (4) into (2), we can obtain (1). ☐

Proposition 2: (RA Failure Probability of IoT Devices With Low-Priority): For the given n_h, n_l, k_h, k_l and M, the RA failure probability of a single IoT device with high-priority, p_l, is derived as follows:

$$p_l = \sum_{m=0}^{k_h} (-1)^m \left(\frac{(M-k_h)!\,(M-m)!}{(M-m-k_h)!M!} \right)^{n_h} \times \left(\frac{(M-k_l)!\,(M-m)!}{(M-m-k_l)!M!} \right)^{n_l-1} \binom{k_l}{m}. \quad (5)$$

[7] In our proposed technique, even though each IoT device experiences a few preamble collisions it can successfully complete the RA procedure due to the preamble diversity effect [19]. Thus, we use the term 'failure' rather than 'collision'. Note that mis-detections due to the poor channel condition may affect the RA performance but this can be under control by open-loop power control such as power ramping and thus we do not consider this physical layer aspect in our analytical framework.

TABLE 1. Simulation parameters and values.

Parameters	Values
Number of IoT devices with high-priority (n_h)	1, 2
Number of IoT devices with low-priority (n_l)	$1 \sim 8$
Number of simultaneously transmitted preambles for high-priority (k_h)	$1 \sim 8$
Number of simultaneously transmitted preambles for low-priority (k_l)	1, 2
Number of available RA preambles (M)	$20 \sim 64$

Proof: We newly define Ω_l as the entire sample space which includes all possible outcomes when each of n_h devices independently selects k_h preambles and each of $n_l - 1$ devices independently selects k_l preambles. Then, p_l is given by

$$p_l = \frac{n(\mathcal{A}_0)}{n(\Omega_l)} = 1 - \frac{n\left(\bigcup_{m=1}^{k_h} \mathcal{A}_m\right)}{n(\Omega_l)}. \tag{6}$$

The term $n\left(\bigcup_{m=1}^{k_h} \mathcal{A}_m\right)$ can be obtained as follows:

$$n\left(\bigcup_{m=1}^{k_h} \mathcal{A}_m\right) = \sum_{m=1}^{k_h} \binom{M-m}{k_h}^{n_h} \times \binom{M-m}{k_l}^{n_l-1} \binom{k_l}{m} (-1)^{m-1}, \tag{7}$$

and the term $n(\Omega_l)$ can be obtained as follows:

$$n(\Omega_l) = \binom{M}{k_h}^{n_h} \binom{M}{k_l}^{n_l-1}. \tag{8}$$

By plugging (7) and (8) into (6), we can obtain (5). □

As mentioned in Section IV-B, our proposed technique can be considered as a generalized version of the RA procedure where the number of simultaneously transmitted preambles is relaxed according to the access priority.

Remark 1: When $k_h = k_l = k$, (1) and (5) are reduced to

$$p_h = p_l = \sum_{m=0}^{k} (-1)^m \left(\frac{(M-k)!\,(M-m)!}{(M-m-k)!M!}\right)^{n-1} \binom{k}{m}, \tag{9}$$

which achieves the same RA failure probability with the RAP technique, where $n = n_h + n_l$ [19].

Remark 2: When $k_h = k_l = 1$, (1) and (5) are reduced to

$$p_h = p_l = 1 - \left(1 - \frac{1}{M}\right)^{n-1}, \tag{10}$$

which is the same with the conventional collision probability as in [10], where $n = n_h + n_l$.

VI. NUMERICAL RESULTS

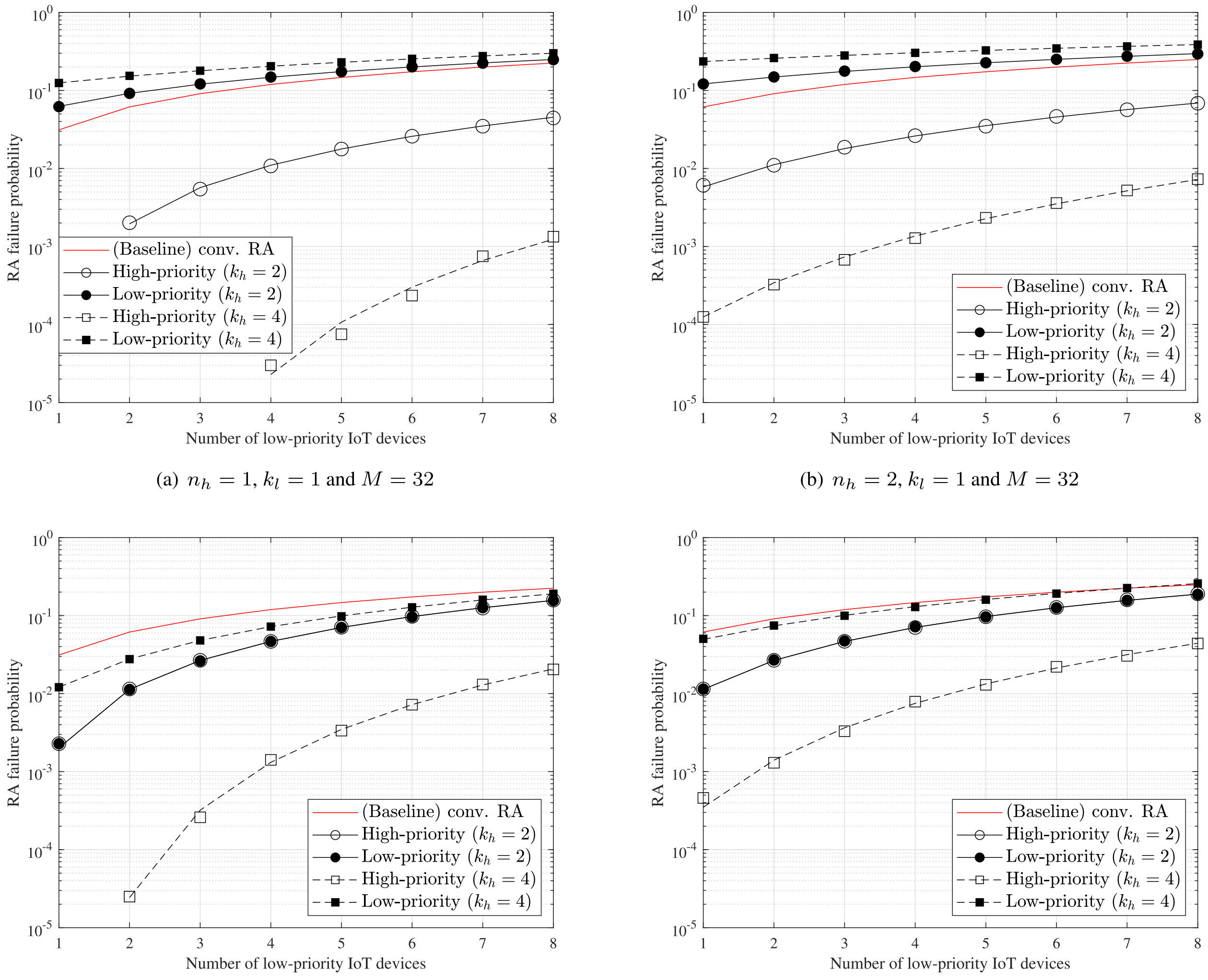
In this section, we evaluate the performance of our proposed technique in terms of RA failure probability. We perform extensive computer simulations with MATLAB, where specific simulation parameters are listed in Table1 [19]. Considering two types of access priorities, we categorize the entire IoT devices into two groups with different access priorities: high and low priorities. We assume that the number of IoT devices with high-priority is much smaller than that of the IoT devices requiring low access priority, i.e., $n_h < n_l$, and, thus, we conservatively set the values of n_h and k_l as denoted in Table 1.[8] We do not consider the physical layer aspects such as erroneous detection (i.e., false alarm) and misdetection. In all figures, lines and markers depict analysis and simulation results, respectively.

Fig. 4 shows the RA failure probabilities for varying the number of IoT devices with low-priority, n_l, in several scenarios. Performance of the high-priority devices will be comprehensively examined in the situation where the devices with low-priority coexist. Note that we do not change the value of M, i.e., $M = 32$, in Fig. 4. The effect of M on the performance is further investigated in Fig. 6. Furthermore, the effect of k_h can be investigated in Fig. 4 which will be further investigated in Fig. 5. For fair comparison, we also plot the performance of the conventional RA procedure as a baseline scheme. The conventional RA procedure does not have any functionality of access priority provisioning, and thus, all IoT devices using the conventional one achieve the same performance even they have different access priority.

In detail, Fig. 4 (a) shows the result of the scenario when $(n_h, k_l) = (1, 1)$. As the value of n_l increases, both the RA failure probabilities of IoT devices with high and low priorities increase since the collision increases due to the increased contention participants. However, it is clearly observed that the access performance is surely differentiated according to the access priority. As the value of k_h increases, the RA failure probability of the device with high-priority significantly decreases at the sacrifice of the access performance of the low-priority devices. Particularly, it is worth noting that when a single IoT device with high-priority contends with other devices with low-priority, i.e., $n_h = 1$ and $n_l > 0$, the case that the device with high-priority does not fail to access the networks may occur.[9] In other words, when the total number of used preambles by the IoT devices with low-priority does not exceed k_h, the RA failure-less region can be observed. This implies that there exists at least a preamble exclusively utilized by the device with high-priority.

[8] Typically, the n_l value may not be large even in an IoT scenario (e.g., $1 \sim 10$), since the activity of IoT devices is expected to be low [22]. For example, if 100, 000 IoT devices attempt RAs for every 5 minutes on average when the PRACH period and the number of available RA preambles are set to 10 (ms) and 32, respectively, n_l becomes 3.76 on average [10].

[9] We assume that the RA failures are mainly caused by the collisions.



(a) $n_h = 1, k_l = 1$ and $M = 32$

(b) $n_h = 2, k_l = 1$ and $M = 32$

(c) $n_h = 1, k_l = 2$ and $M = 32$

(d) $n_h = 2, k_l = 2$ and $M = 32$

FIGURE 4. RA failure probabilities for varying n_l under several (n_h, k_l) combinations when $M = 32$.

Fig. 4 (b) shows the result of the scenario when $(n_h, k_l) = (2, 1)$. In this scenario, overall observations are consistent with the scenario in Fig. 4 (a). However, the failure-less region for the devices with high-priority cannot be observed unlike the result in Fig. 4 (a) since we consider the case when $n_h = 2$. When two devices with high-priority attempt the RAs at the same time, the case that both devices with high-priority select the totally identical preambles may occur regardless of the existence of the devices with low-priority. This is why the failure-less region cannot be observed when $n_h > 1$.

In Fig. 4 (c) and Fig. 4 (d), we consider the scenarios when the devices with low-priority use dual preambles not a single preamble, i.e., $k_l = 2$. Since dual-preamble transmissions help to achieve the preamble diversity effect [19], both the devices with high and low priorities can achieve better performance compared to the conventional one. In addition, it is also found that the functionality of access priority provisioning works well when $k_h \neq k_l$. On the contrary, when $k_h = 2$, the entire devices regardless of the access priority simultaneously transmit the same number of preambles, i.e., $k_h = k_l = 2$, both devices in different access priority groups naturally achieve the same RA performance as described in Remark 1. This result coincides with that of the RAP technique with the same parameter setting (Refer to details in [19]). Note that the failure-less region of the device with high-priority is also observed in Fig. 4 (c).

Fig. 5 shows the RA failure probability for varying the number of simultaneously transmitted preambles from the IoT devices with high-priority, k_h, when $n_l = 1$, $k_l = 1$ and $M = 32$. Since k_l is set to 1, the RA failure probability of the IoT devices with high-priority can be significantly reduced as k_h increases while the IoT devices with low-priority suffer from slight increase in the RA failure probability. This observation can be also found in all figures in Fig. 4. Note that when $k_h = 1$, both devices with high and low priorities achieve the same RA failure probability since $k_h = k_l = 1$,

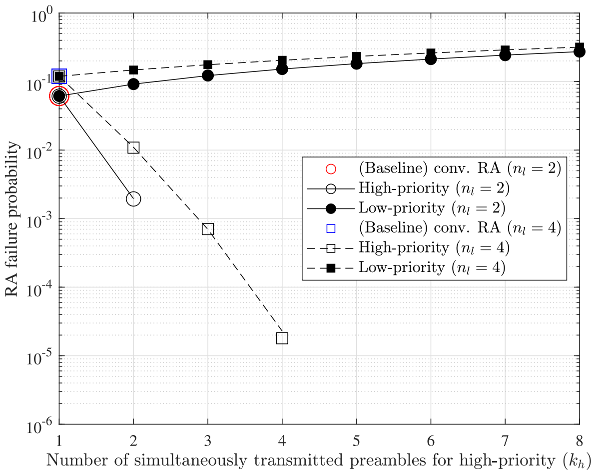


FIGURE 5. RA failure probability for varying k_h when $n_h = 1$, $k_l = 1$ and $M = 32$.

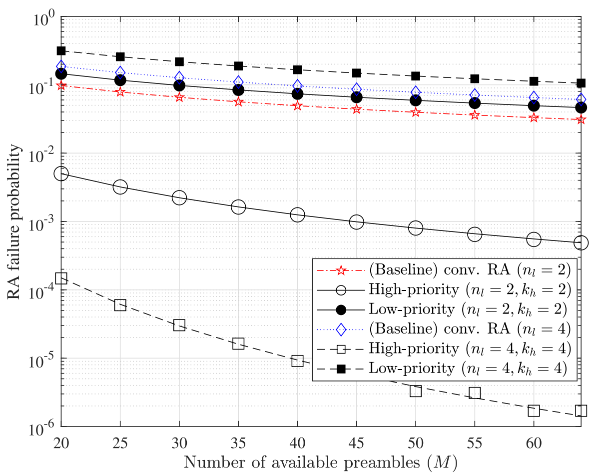


FIGURE 6. RA failure probability for varying M when $n_h = 1$ and $k_l = 1$.

and its value is also the same with the collision probability of the conventional one as described in Remark 2. Note that the failure-less region is also observed.

Finally, Fig. 6 shows the RA failure probability for varying M when $n_h = 1$, $k_l = 1$ and several (n_l, k_h) combinations. More contention resources, i.e., RA preambles, lower RA failure probability can be readily expected. From the results, we investigate that the RA failure probability decreases as M increases and the functionality of access priority is well provisioned.

VII. CONCLUSION

In this paper, we proposed a novel access priority provisioning technique to support different access requirements from diverse internet-of-things (IoT) applications in cellular networks. Our proposed technique can be applied to the RA procedure which helps to configure prioritized cellular IoT networks. A key feature of our proposed technique is that each IoT device differentiates the number of simultaneously transmitted preambles at the first step of the RA procedure. Since simultaneous transmission of multiple preambles (i.e., RA parallelization) can achieve the diversity effect during the access phase (i.e., RA procedure), the IoT devices using more preambles can achieve better access performance compared to those using fewer preambles. We mathematically analyzed our proposed technique in terms of RA failure probability and validated our analytical framework with extensive simulations. From the results, we verified the feasibility that our proposed technique can be used to support access priority during the access phase without significant modifications to the conventional one.

Since the performance gain of our proposed technique mainly comes from the parallelization of the RA procedure which requires more signalings and radio resources. Thus, our proposed technique should be further comprehensively investigated in terms of radio resource efficiency and energy consumption, which remains as future work. Furthermore, the generalization of the analytical framework to multi-class scenario and the consideration of the physical-layer aspects during the preamble detection phase may be also challenging issues to be addressed in near future.

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