An Enhanced Random Access With Inter-Frame Successive Interference Cancellation for Stationary Cellular IoT Networks

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***Abstract*—In 5G cellular networks, it is required to accommodate a massive number of Internet-of-Things (IoT) devices in a resource-efficient way. In this letter, we propose a random access with an inter-frame successive interference cancellation (RA-ISIC) for stationary IoT networks. In our proposed scheme, the BS does not discard the collided packets and attempts to recover them through inter-frame SIC operations. We evaluate the performance of our proposed scheme in terms of resource efficiency. Results show that a certain level of system load is required to maximize the efficiency of our proposed scheme, which can be achieved through a probabilistic retransmission (PR) policy. Consequently, our proposed scheme can effectively improve the resource efficiency and can be suitable to accommodate more IoT devices with a smaller amount of resources, compared to the conventional one.**

***Index Terms*—Cellular networks, 5G, random access, successive interference cancellation, resource efficiency.**

I. INTRODUCTION

EVOLUTION of wireless communication technologies toward the 5G enables everything to be connected through IP-based networks, i.e., Internet-of-Things (IoT) [1]. Since most of IoT devices stay out-of-connections with the base station (BS) for saving energy consumption, each IoT device should perform a random access (RA) procedure to establish connection with the BS before uplink transmissions of newly generated packets [2]. Even though each IoT device may sporadically (or intermittently) access the networks [3], the number of RA attempts at a certain RA slot may not be small due to the high density of IoT devices deployed within a cell [4]. Since the current cellular systems were originally designed for human-to-human communications with a few user terminals, a collision problem has been still considered as one of critical bottlenecks to support IoT in cellular networks.

Especially in uplink transmissions, two types of radio resources are utilized during the RA procedure [5]. One is a physical random access channel (PRACH) for transmitting preamble in Step 1 and the other is a physical uplink shared channel (PUSCH) for transmitting data packets (e.g., scheduling or connection request messages) in Step 3. When a certain preamble is used by two or more IoT devices, i.e., preamble collision, they inevitably utilize the same resource while transmitting the packet, i.e., Step 3 message. Consequently, the allocated uplink resource is meaningfully wasted.

Enormous efforts in both academia and industry are devoted to addressing the collision problem [6]–[8]. Ko *et al.* [6] proposed an RA scheme suitable for stationary IoT which focuses on the feature that wireless channel between each IoT device fixed at a certain location and the BS is hardly changed. Kim *et al.* [7] proposed a preamble reuse mechanism, where the identical preamble set can be reused at the spatially separated groups. Park *et al.* [8] proposed an enhanced RA scheme with time-shifted preambles which improves both the collision probability and the fairness. Even though those previous studies may attempt to address a collision problem, however, they still depend on a collision model, where the collided packets are meaningfully discarded, and the resources where the collisions occur are considered as waste.

The RA procedure in cellular networks can be also viewed as a variation of a general random access networks (RANs) [9], e.g., local area networks (IEEE 802.11). There have been studies on improving the system performance with a successive interference cancellation (SIC) [10]–[13]. Casini *et al.* [10] proposed a contention resolution diversity slotted-ALOHA (CRDSA), where each device transmits two or more replicas of each packet in every frame, and the system decodes collided packets through the *intra-frame* SIC. Power-domain SIC was applied to the RA procedure in cellular networks [11], [12], which can be categorized into a special case of the intra-frame SIC without replica transmissions. Ricciato and Castiglione [13] proposed a pseudo-random ALOHA for collision recovery in radio frequency identification (RFID), where the *inter-frame* SIC was introduced. The authors of [13] also addressed the need for the pseudo-random slot selection to perform the inter-frame SIC. We notice that if we efficiently use the stationary condition of IoT devices, the inter-frame SIC can further improve the RA performance in cellular networks.

This letter proposes a random access with an inter-frame successive interference cancellation (RA-ISIC) scheme for stationary IoT networks. With our proposed scheme, the collided packets can be recovered through inter-frame SIC operations and thus the resource efficiency can be significantly improved. Results show that a certain level of system load is required to maximize the efficiency of our proposed scheme and a small number of buffers for storing the previous collided packets are enough to exploit inter-frame SIC operations.

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II. SYSTEM MODEL

We consider a single cell network, where *N* IoT devices are uniformly distributed within a cell coverage. We also consider the stationary deployment scenario [6], where each IoT device is fixed at a certain location. Thus, the wireless channel between each of IoT devices and the BS may not be abruptly changed within a short period [6], [8]. Furthermore, each IoT device attempts its RA procedure following a Poisson distribution where the packet arrival rate is λ. The BS is equipped with a buffer-aided SIC receiver, where *B* is the number of buffers at the BS. When the BS is equipped with *B* buffers, the entire signals (e.g., preambles in Step 1 and data packets in Step 3) in the previous *B* random access cycles can be stored and used for SIC operations. Especially, we consider the inter-frame SIC when decoding packets, i.e., Step 3 messages. During the *B* random access cycles, the wireless channel is assumed to be static due to the stationary deployment assumption of the IoT devices, which implies that the packet can be decoded with the channel state information (CSI) acquired through any uplink demodulation reference signal (DMRS) within the corresponding time period.[1]

In order to trigger the inter-frame SIC with successfully decoded (or, recovered) messages, the BS should have to know the location where the other replicas were transmitted [13]. To address this problem, we use a *pseudo-random preamble selection (PRPS) function* which is known to both each of IoT devices and the BS. The PRPS function can be expressed as $g : (u, r) \to m_{u,r}$, where *u*, *r*, and $m_{u,r}$ represent the user identifier (UID, or equivalently C-RNTI),[2] the number of RA trials, and the preamble index, respectively. After obtaining both *u* and *r* from the successfully decoded packet [15], the BS can backtrack the preamble indices used by the corresponding IoT device during the previous RA attempts. Furthermore, the relationship between the preamble index used in Step 1 and the uplink resource where the Step 3 message is transmitted can be also expressed as a one-to-one function, i.e., $h(m) : m \to M$, where *M* represents the location of the uplink resource.

For example, after the BS acquires *u* and *r* from the successfully decoded packet, it can backtrack the previously used preamble indices through the PRPS function, i.e., $\{(u,1) \xrightarrow{g} m_{u,1}, \ldots, (u, r-1) \xrightarrow{g} m_{u,r-1}\}$. Accordingly, the BS can also backtrack the previously used uplink resources using the one-to-one relationship, i.e., $\{m_{u,1} \xrightarrow{h} M_{u,1}, \ldots, m_{u,r-1} \xrightarrow{h} M_{u,r-1}\}$.

Even though the forward error correction (FEC) is considered, the packet recovery (decoding) during the SIC operations may not be perfect due the error propagation phenomenon [16]. In order to consider the effect of errors during the SIC operations on the performance, we newly introduce a notion of packet recovery error probability, which is denoted by p_{e}. When a packet is collided with other packets at a given radio resource, we assume that it can be recovered with a probability of $1 - p_{\mathrm{e}}$ through SIC operation under the condition that other collided packets are ready at the BS. It is also obvious that the corresponding packet cannot be recovered when other collided packets are not available. It is worth noting that $p_{\mathrm{e}} = 0$ implies that the entire SIC operations are perfectly performed and $p_{\mathrm{e}} = 1$ implies that the entire SIC operations are failed.

III. RANDOM ACCESS WITH AN INTER-FRAME SUCCESSIVE INTERFERENCE CANCELLATION

In this section, we propose a random access with an inter-frame successive interference cancellation (RA-ISIC) and provide detailed explanations on the proposed scheme.

A. Probabilistic Successive Interference Cancellation

Let $y_{t,f}$ represent the received signal on resource (*t*, *f*), which can be expressed as:

$$\begin{aligned} y_{t,f} &= \sum_{k\in\mathcal{K}_{t,f}} h_k x_k + w \\ &= h_l x_l + \sum_{k\in\mathcal{K}_{t,f}\setminus\{l\}} h_k x_k + w, \end{aligned} \tag{1}$$

where x_k, h_k, and *w* represent the device *k*'s packet, the channel between device *k* and the BS, and the Gaussian noise, respectively, and $\mathcal{K}_{t,f}$ represents the set of devices transmitting packets via resource (t, f). Conventionally, the collisions are regarded as destructive and irrecoverable. Thus, the BS discards the collided packets and the entire devices in $\mathcal{K}_{t,f}$ have to retransmit their packets. However, the collisions can be just regarded as summations of packets, so they can be efficiently reused during the subsequent decoding process. In principle, if $y_{t,f}$ is buffered, even though the device *l* does not retransmit its packet, its packet can be recovered from the interference-cancelled signal, i.e., $y_{t,f} - \sum_{k\in K_{t,f}\setminus\{l\}} h_k x_k$, after the BS retrieves other packets from $\mathcal{K}_{t,f}\setminus\{l\}$.

As we mentioned in the system model, the SIC operations may not be perfect due to several reasons such as error propagations. Considering such practical issues, in our system model, the device *l*'s packet, i.e., x_l, is considered to be recovered following a probabilistic model (please refer to (1)). Let s denote a random variable which follows a uniform distribution, i.e., $s \sim \mathrm{U}[0, 1]$. In our probabilistic SIC model, when $s \leq 1 - p_{\mathrm{e}}$, x_l is assumed to be recovered from $y_{t,f} - \sum_{k\in K_{t,f}\setminus\{l\}} h_k x_k$ after retrieving all the other collided packets, i.e., x_k for all $k \in K_{t,f}\setminus\{l\}$. In other words, even though the BS retrieves all the other collided packets, the remaining packet may not be successfully recovered through the SIC operation due to the packet recovery error (e.g., caused by the accumulation of errors during the SIC operations).

B. Overall Procedure

The procedure of the proposed RA-ISIC scheme consists of 5 steps, and the details of each step are as follows:

- *(Step 1) Preamble Transmissions:* Each IoT device selects a preamble sequence following the PRPS function and transmits it on PRACH. It is noteworthy that each IoT

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[1] The uplink demodulation reference signal (DMRS) is time multiplexed within each of packets for coherent decoding and multiple orthogonal DMRSs are conveyed using the same time-frequency resource [5], [14].

[2] To use the PRPS function, each IoT device should know its identifier in advance. We assume that each IoT device knows its own identifier (e.g., C-RNTI) through the previous communications with the BS and stores it for future usage.

device must attempt its first RA with a probability of 1.[3] In case of RA reattempts, on the contrary, each IoT device transmits the selected preamble with a probability of p_t, which is called a probabilistic retransmission (PR) policy. With the PR policy, even though each IoT device does not reattempt RAs, its previously transmitted packets, i.e., Step 3 message, during the previous RA attempts can be recovered through the inter-frame SIC operations.

- *(Step 2) Random Access Response (RAR):* The BS detects which preambles are active based on the power delay profile (PDP) of the received signal through PRACH. If there exist any peaks (i.e., impulses) in the *m*-th preamble detection zone, the BS regards that the *m*-th preamble is active. According to the detection result, the BS sends RA responses (RARs), where each RAR contains an RA preamble index (RAPID), i.e., *m*, uplink grant (UG), i.e., *M*, timing alignment (TA) value, and C-RNTI. Each IoT device finds its RAR by comparing the RAPID used in Step 1 and the RAPID contained in the received RAR. Note that when two or more IoT devices use the same preamble, i.e., preamble collision, they received the same RAR. Consequently, they use the same uplink resource when they transmit their packet in the subsequent step, which inevitably results in a packet collision.
- *(Step 3) Packet Transmissions:* Each IoT device transmits a packet (e.g., scheduling or connection request message) on the uplink resource in the PUSCH, which is indicated by the UG contained in the received RAR.
- *(Step 4) Inter-Frame Successive Interference Cancellation (ISIC):* If the BS succeeds in decoding the packet, it backtracks the location where the previous transmissions occurred. Then, the BS subtracts the replicas of the decoded message from the locations where previous messages are transmitted. If another message is recovered through the inter-frame SIC operation, the result propagates to both reverse and forward directions and triggers the subsequent decoding of other messages. The inter-frame SIC operations are iterated until the BS is unable to decode more messages. This step can be implemented with a message-passing algorithm in Algorithm 1. Note that the complexity of the algorithm increases in proportion to the number of buffers.
- *(Step 5) Acknowledge:* The BS broadcasts the identifiers of the IoT devices, whose packets are successfully decoded after the inter-frame SIC.

Fig. 1 shows an example of the inter-frame SIC operations during the RA procedure in cellular networks when the BS is equipped with the SIC receiver with two buffers. The Step 3 message of IoT device *A* is decoded at the *i*-th RA cycle, enabling the removal of its replica from the resource M_2 at the $(i-1)$-th RA cycle and the subsequent recovery of the Step 3 message of IoT device *C*. The recovery of IoT device *C*'s message also enables the removal of its replica from the resource M_1 at the $(i-2)$-th RA cycle and thus the Step 3 message of IoT device *D* can be recovered. In the same way, the IoT device *E*'s message is also recovered. In this example, all 5 IoT devices succeed in their RAs using 5 resources. It is shown that the *resource efficiency*[4] can be effectively improved from 0.4($=$ 2/5) to 1($=$ 5/5) with our proposed scheme.

Algorithm 1 Message-Passing Algorithm

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Notations
  · $S(\cdot)$ : SIC operation
  · $\mathcal{R}_{i\to i-1}$ :
      Reverse messages from the i-th frame to the (i-1)-th frame
  · $\mathcal{F}_{i\to i+1}$ :
      Forward messages from the i-th frame to the (i+1)-th frame
  · $\mathcal{D}^R_i$ :
      Decoded messages during the reverse ISIC at the i-th frame
  · $\mathcal{D}^F_i$ :
      Decoded messages during the forward ISIC at the i-th frame
Input : $\mathcal{D}_i$   // Decoded packets at the i-th frame
Output : $\mathcal{O}$   // Final decoded packets after SIC operations

if $\mathcal{D}_i = \phi$ then
    do nothing
else
    Reverse message-passing:
    $\mathcal{R}_{i\to i-1} = \mathcal{D}_i$   // Triggering the reverse ISIC
    for $j = 1$ to B do
        $\mathcal{D}^R_{i-j} = S(\mathcal{R}_{i-(j-1)\to i-j})$
        $\mathcal{R}_{i-j\to i-(j+1)} = \mathcal{R}_{i-(j-1)\to i-j} \cup \mathcal{D}^R_{i-j}$
    end for
    Forward message-passing:
    $\mathcal{F}_{i-B\to i-(B-1)} = \mathcal{D}^R_{i-B}$   // Triggering the forward ISIC
    for $j = B$ to 1 do
        $\mathcal{D}^F_{i-(j-1)} = S(\mathcal{F}_{i-j\to i-(j-1)})$
        $\mathcal{F}_{i-(j-1)\to i-(j-2)} = \mathcal{F}_{i-j\to i-(j-1)} \cup \mathcal{D}^F_{i-(j-1)}$
    end for
    Broadcasting the decoding results:
    $\mathcal{O} = \mathcal{D}_i \cup (\bigcup_{j=i-B}^{i-1} \mathcal{D}^R_j) \cup (\bigcup_{j=i-(B-1)}^{i} \mathcal{D}^F_j)$
end if
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TABLE I
SIMULATION PARAMETERS AND VALUES

Parameters	Values
Number of IoT devices (N)	$0 \sim$ 200,000
RA arrival rate (λ)	1/600 (sec^{-1})
Number of preambles	8
The number of buffers (B)	$1 \sim 5$
The number of maximal transmissions	10
PRACH period	10 (ms)

IV. NUMERICAL RESULTS

We perform system-level simulations using a process-oriented discrete-event simulation package, CSIM, with the parameters specified in Table I [2]. We evaluate the performance of our proposed scheme in terms of resource efficiency. For fair comparison, we use the conventional RA scheme with a probabilistic retransmission (PR) policy as a baseline scheme. It is noteworthy that the baseline scheme operates as the same with the conventional RA scheme when $p_t = 1$.

Fig. 2 shows the resource efficiency for varying the transmit probability, p_t, when p_{e} is set to 0. In this case, the

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[3] Each IoT device should send at least a packet to the BS for expecting it to be recovered through SIC without retransmitting the same packet.

[4] Resource efficiency is defined as the ratio of the amount of effectively utilized resources to the total amount of allocated resources.

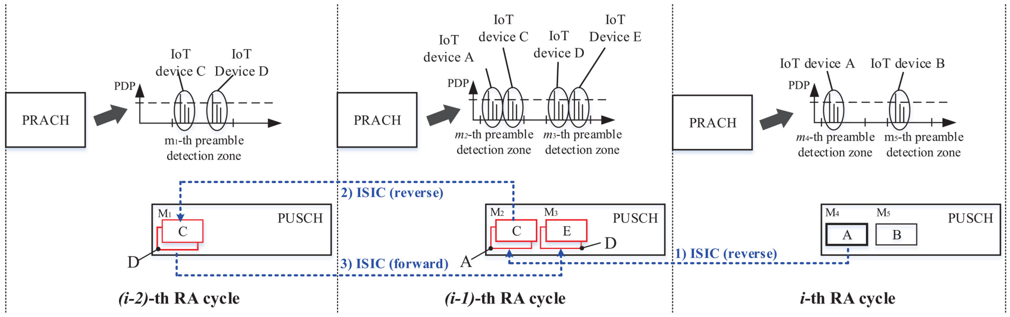

Fig. 1. An example of inter-frame SIC operations during RA procedure in cellular networks when the BS is equipped with the SIC receiver with two buffers.

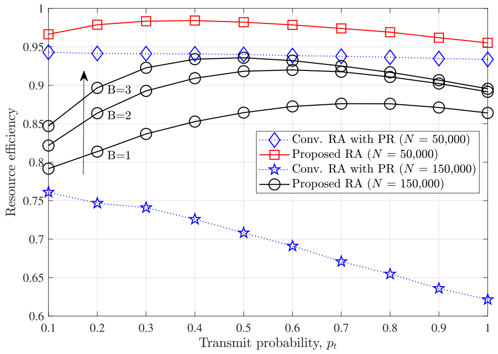

Fig. 2. Resource efficiency for varying the transmit probability when $p_e = 0$.

performance of our proposed scheme can be upper bound from the MAC layer perspective since we do not consider packet recovery errors during the SIC operations, i.e., $p_e = 0$. As p_t increases, a gradual decrease in the resource efficiency is observed with the baseline scheme and the deterioration becomes much severer as N increases. On the contrary, the resource efficiency of the proposed scheme shows a convex feature with regard to p_t. When p_t is small, each IoT device may be hard to attempt RAs due to the small p_t value. In this case, the BS may not have sufficient buffered signals and thus the inter-frame SIC operations hardly occur. When p_t is large enough, even though the BS has sufficient buffered signals and attempts to execute inter-frame SIC operations, the collided packets may be hardly recovered since the same uplink resource may be unintentionally shared by too many devices due to severe collisions. From the observation, we can find that a certain level of system load, which generates sufficient enough but not too much collisions, is required to perform inter-frame SIC operations. Thus, it is important to carefully set p_t.

Furthermore, the number of buffers, B, also affects the resource efficiency, since it is directly related to the amount of buffered signals. However, the amount of improvement in the resource efficiency gradually decreases as B increases and thus a few buffers seem to be enough to exploit the inter-frame SIC operations, e.g., $B \leq 3$.[5] Table II summarizes the maximally achievable resource efficiency according to B for various p_e values, where the resource efficiency is denoted by η. It is also shown that the overall performance is degraded due to the packet recovery errors as p_e increases.

TABLE II
RESOURCE EFFICIENCY ACCORDING TO B FOR VARIOUS p_e VALUES

	$p_e = 0$		$p_e = 0.1$		$p_e = 0.2$	
B	$p_t^\star$	$\eta(\%)$	$p_t^\star$	$\eta(\%)$	$p_t^\star$	$\eta(\%)$
1	0.7	87.6	0.7	86.2	0.7	84.1
2	0.6	92.0	0.6	91.1	0.6	90.0
3	0.5	93.6	0.5	92.9	0.5	92.0
4	0.4	94.4	0.4	93.8	0.4	93.1
5	0.3	94.8	0.3	94.4	0.3	93.6

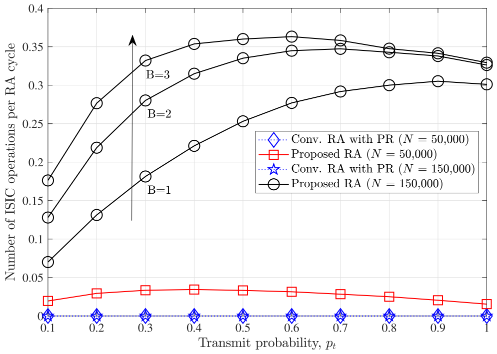

Fig. 3. Average number of inter-frame SIC operations per RA cycle for varying the transmit probability when $p_e = 0$.

Fig. 3 shows the average number of inter-frame SIC operations per RA cycle for varying p_t when $p_e = 0$. From the observation, we can find that the number of inter-frame SIC operations is highly related with the resource efficiency as shown in Fig. 2 and a few inter-frame SIC operations are enough to significantly improve the resource efficiency. When N = 150,000, $B = 3$, and $p_t = 0.5$, the proposed scheme performs approximately 0.36 inter-frame SIC operations per RA cycle, which results in approximately 22.73% increase of the resource efficiency, compared to the baseline scheme as shown in Fig. 2. It is noteworthy that $p_t{}'$ which maximizes the average number of inter-frame SIC operations is similar but different from $p_t^\star$ which maximizes the resource efficiency. This is because there exist successfully decoded packets without inter-frame SIC operations which also contributes to the increase of the resource efficiency.

Fig. 4 shows the effect of packet recovery errors on the resource efficiency when N and p_t are set to 150,000 and 1.0, respectively. Since we consider a probabilistic SIC model as described in Section III-A, the resource efficiency is deteriorated as p_e increases. It is noteworthy that $p_e = 1$ implies that the SIC operations cannot work properly and thus the resource

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[5] In practice, increasing B may cause additional decoding complexity at the BS and degrade the performance of SIC operations due to the possible channel variations and error propagations.

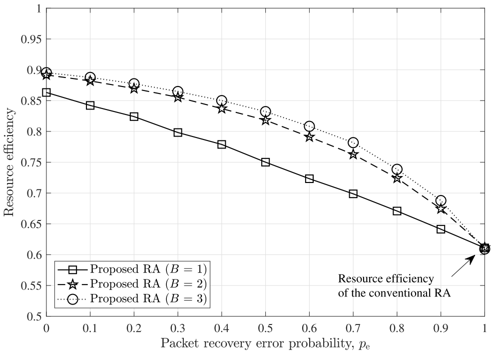

Fig. 4. Resource efficiency for varying the packet recovery error probability, p_e, when $N =$ 150,000 and $p_t = 1$.

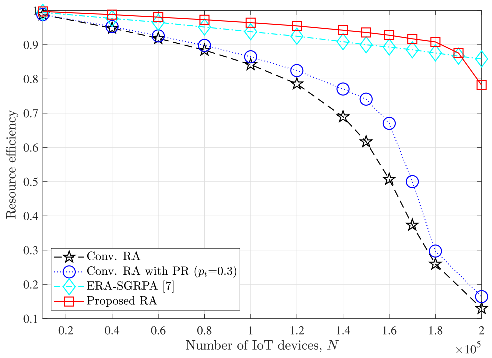

Fig. 5. Resource efficiency for varying the number of IoT devices when $B = 3$ and $p_e = 0$.

efficiency converges to the value that can be achieved via the conventional RA scheme.

Fig. 5 shows the resource efficiency for varying the number of IoT devices, N, when $B = 3$ and $p_e = 0$. As a comparison group, we additionally plot the result of an enhanced RA with spatial group based reusable preamble allocation (ERA-SGRPA) scheme [7] as one of the state-of-the-art schemes, which enables RA preambles to be reused and logically increases the amount of RA preambles. In case of our proposed scheme, the optimal $p_t^\star$ which maximizes the resource efficiency for each N value is applied. As N increases, the resource efficiency shows a tendency of decrease regardless of schemes, since the collision increases as N increases. Reducing p_t of the baseline scheme, the slight improvement of the resource efficiency can be achieved, since the PR policy has an impact on reducing system load and alleviating collisions [17]. Due to the logically increased contending resources, the ERA-SGRPA scheme reduces the collisions and thus the resource efficiency can be also improved. With our proposed scheme, the amount of resources which are wasted due to collisions decreases since our proposed scheme enables the BS to recover the collided packets with the inter-frame SIC operations. Thus, the system can achieve and maintain high resource efficiency even though N increases. It is noteworthy that our proposed scheme can achieve a higher resource efficiency compared to the competitive ERA-SGRPA scheme [7].

If we set a target resource efficiency to 95%, the baseline scheme can accommodate approximately 30,000 IoT devices, on the other hand, the proposed scheme can accommodate approximately 120,000 IoT devices. It is shown that adopting a few more buffers can significantly increase the number of supportable stationary IoT devices.

V. CONCLUSION

In this letter, we proposed a random access with a inter-frame successive interference cancellation (RA-ISIC) scheme for supporting stationary IoT devices in cellular networks. Our proposed scheme efficiently recovers the collided packets through inter-frame SIC operations and thus the resource efficiency can be improved. Results show that a certain level of system load is required to maximize the efficiency of our proposed scheme and a small number of buffers for storing the previous collided packets are enough to exploit inter-frame SIC operations. We conclude that our proposed scheme is suitable to accommodate more IoT devices in a resource-efficient way, compared to the conventional one.

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