논문 22-47-07-03 The Journal of Korean Institute of Communications and Information Sciences '22-07 Vol.47 No.07
https://doi.org/10.7840/kics.2022.47.7.926

Resource Efficiency Analysis of Random Access Parallelization Technique for Cellular IoT Networks

Taehoon Kim◆, Inkyu Bang°

ABSTRACT

Recently, a random access parallelization (RAP) technique for cellular internet-of-things (IoT) networks was proposed in [1], and RA failure probability was the performance metric of interest. Even though the performance gain in terms of the RA failure probability comes from the sacrifice of the resource efficiency, this point was not well discussed in [1]. We believe that providing supplementary descriptions on the RAP technique from the viewpoint of the resource efficiency is highly required to comprehensively understand for the RAP technique. To this end, in this letter, we newly provide the mathematical analysis on the resource efficiency of the RAP technique and verify its validity through simulations. Finally, we formulate an optimization problem taking the resource efficiency into account and numerically find its solution.

Key Words : Cellular IoT, Random access parallelization, Resource efficiency

Ⅰ. Introduction

In cellular networks, each device should perform contention-based four-steps of random access (RA) procedure to establish connection with a base station (BS). For years, a number of studies have made efforts to resolve the collision problems during the RA procedure[1-3], since the occurrence of collisions increases as the number of contending participants such as IoT devices increases.

Recently, an RA parallelization (RAP) technique was proposed to tackle the corresponding problem[1], where the key feature is to relax the constraint on the number of preambles transmitted during the first step of the RA procedure. With the RAP technique, each device can simultaneously transmit multiple preambles at an RA slot, which implies that each device can perform multiple RAs at the same time in parallel. Accordingly, the occurrence of RA failures due to collisions can be significantly reduced since our proposed technique is effective to prevent the case that preambles used by a certain device are fully collided with preambles selected by other devices.

On the contrary, the RAP technique causes excessive signalings approximately proportion to the value of k, which is the key parameter controlling the number of simultaneously transmitted preambles during the first step, since each of devices performs multiple k RAs in parallel. Thus, the BS should spend more radio resources correspondingly. The fact that the performance gain comes from the sacrifice of the resource efficiency was not discussed in detail in [1]. To provide comprehensive descriptions on the RAP technique, we newly provide the mathematical analysis on the resource efficiency of the RAP technique and formulate an optimization problem to minimize RA failure probability considering the resource efficiency aspect as well. Through simulations, we verify the validity of analytical approach and numerically find the solution of the optimization problem.

Ⅱ. Resource Efficiency Analysis

Since our proposed technique triggers k RAs in parallel, additional signalings, e.g., redundant transmissions of Step 3 message (i.e., connection

---

※ 이 논문은 정부(과학기술정보통신부)의 재원으로 한국연구재단의 지원을 받아 수행된 연구임 (No. 2020R1G1A1101176).

◆ First Author : (ORCID:0000-0002-9353-118X)Hanbat National University Department of Computer Engineering, thkim@hanbat.ac.kr, 조교수, 정회원
° Corresponding Author : (ORCID:0000-0001-7109-1999)Hanbat National University Department of Intelligence Media Engineering, ikbang@hanbat.ac.kr, 조교수, 정회원

논문번호 : 202205-063-A-LU, Received April 28, 2022; Revised May 24, 2022; Accepted May 24, 2022

request message), are required, and, thus, the excessive use of radio resource is inevitable. We often use a definition of radio resource efficiency as a ratio of the number of RA-success devices to the amount of allocated uplink/downlink resources[3], which can quantify how many devices can be efficiently accommodated through a given amount of radio resources. We consider n devices participating in their RAs at a certain RA slot. With the RAP technique, each device triggers k RAs in parallel by simultaneously sending randomly selected k preambles among M preambles during the first step.

Let η denote the resource efficiency, which is expressed as $\eta = \frac{n_S}{n_A}$ where n_S and n_A represent the number of RA-success devices among n devices and the total amount of unit resources used to respond to the RA attempts from n devices, respectively. In detail, $n_S = n \times (1-p_f)$ where p_f is the RA failure probability, which is the probability that the entire preambles sent by a certain device are used by other devices at the same time. p_f can be calculated as

$$p_f = \sum_{m=0}^{k} (-1)^m \left(\frac{(M-k)!(M-m)!}{(M-m-k)!M!} \right) \binom{k}{m}. \tag{1}$$

Proof. See[1]. □

Furthermore, n_A can be expressed as

$$n_A = M \times \left\{ 1 - \prod_{m=1}^{k} \left(\frac{M-m}{M-(m-1)} \right)^n \right\}. \tag{2}$$

Note that n_A is proportional to the amount of detected preambles since the BS allocates uplink resources through RA responses (RARs) in response to the detected preambles.

Now, we are going to newly define the RAP gain as a ratio of the performance gain from the RA failure probability to the performance loss in the resource efficiency. To this end, we first define the performance gain of the RAP technique compared to the conventional RA scheme from the perspective of RA failure probability as $\frac{p_c}{p_f}$ where p_c represents the collision probability of the conventional RA scheme. Similarly, we define the performance loss of the RAP technique compared to the conventional one from the viewpoint of the resource efficiency as $\frac{\eta_c}{\eta}$ where η_c represents the resource efficiency of the conventional one. Finally, the RAP gain can be expressed as in dB scale as

$$\eta = 10 \times \left\{ \log \frac{p_c}{p_f} - \log \frac{\eta_c}{\eta} \right\}. \tag{3}$$

It is worth to note that η quantifies the advantages of the RAP technique against shortcomings of it, and, thus, it can play an important role as a reference to determine whether to apply the RAP technique or not. Consequently, we newly formulate an optimization problem to find optimal k minimizing RA failure probability while considering resource efficiency as follows:

$$\text{(P1)} \quad \begin{aligned} & k^* = \arg\min p_f \\ & s.t. \ \zeta \geq 0. \end{aligned} \tag{4}$$

Ⅲ. Numerical Results & Discussions

We perform simulations with MATLAB to evaluate the performance of the RAP technique in terms of resource efficiency and verify the validity of our analysis. The conventional RA scheme is used as a baseline scheme[4], which is denoted as the case of the RAP technique with $k=1$ in the following figures. Moreover, we use lines and markers to indicate the analytical and simulation results, respectively.

Fig. 1 shows the resource efficiency for several k values when n varies from 2 to 10, and M is given by 32. The resource efficiency of the conventional RA scheme decreases as n increases since n_S decreases due to increase in the occurrence of collisions. On the contrary, the performances of the RAP technique obviously exhibit different trend from the conventional one regardless of k values.

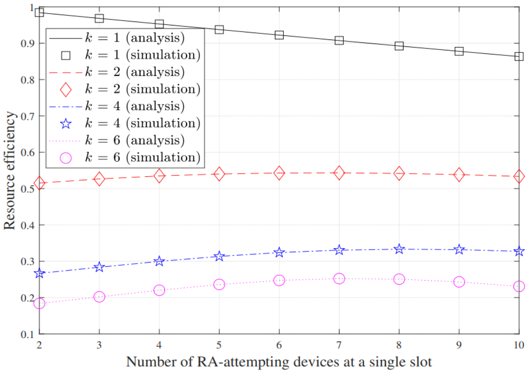

Fig. 1. Resource efficiency for varying n

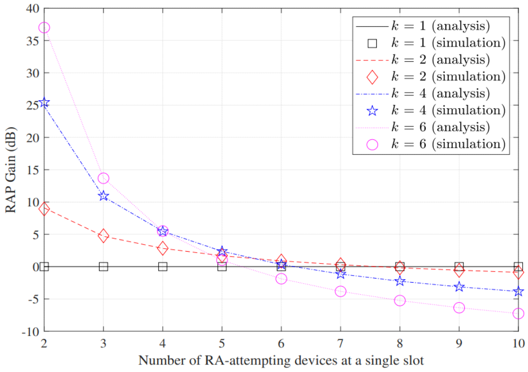

Fig. 2. RAP gain for varying n

Table 1. k^* of (P1) according to n when $M=32$

-	conv. RA [4]	RAP [1]		RAP with ζ		
n	p_c	$k^\star$	p_f	$k^\star$	p_f	ζ(dB)
2	0.031	8	9.5×10^{-8}	8	9.5×10^{-8}	46.79
3	0.062	8	3.8×10^{-4}	8	3.8×10^{-4}	14.33
4	0.091	6	0.060	6	0.060	5.48
5	0.119	5	0.022	5	0.022	0.96
6	0.147	4	0.048	**3**	**0.052**	0.32
7	0.173	3	0.081	**2**	**0.097**	0.29
8	0.119	3	0.126	**1**	**0.119**	0
9	0.224	3	0.153	**1**	**0.224**	
10	0.249	2	0.188	**1**	**0.249**	

When the load of the RA slot is not heavy, i.e., small values of n, the occurrence of RA failures slightly increases even n increases thanks to the low RA failure probability achieved by the RAP technique, and, thus, the resource efficiency does not decrease unlike the conventional one even n increases. However, when n is not small, the resource efficiency decreases as n increases since the occurrence of RA failures rapidly increases due to high RA failure probability. This coincides the result that the performance gain of the RAP technique cannot be expected when n is not small. The resource efficiency is also inversely proportional to the value of k and thus the resource efficiency decreases as k increases regardless of n values.

Fig. 2 shows the RAP gain for several k values when n varies from 2 to 10, and $M=32$. The conventional scheme exhibits zero value for all n since it is used as a reference. From the results, the RAP technique has operating region for each k value that deserves to sacrifice the resource efficiency for achieving significant performance enhancement in RA failure probability. When $M=32$, the operating region of the RAP technique with $k=2$ is $2 \leq n \leq 7$.

Table I summarizes the solutions of **(P1)** for several n values when $M=32$. From the results, **(P1)** finds obviously different solutions compared to the problem in [1], and the meaningful observation is that the value of k should be chosen more conservatively when considering resource efficiency as well. With consideration of the resource efficiency aspect, the RAP technique cannot enjoy the expected performance gain in terms of RA failure probability and should operate in the conventional manner, i.e., $k^*=1$, when the load exceeds beyond a certain point.

With several numerical examples, we verified the validity of our mathematical approach regarding the resource efficiency. Moreover, we found optimal operating parameter, k^*, considering the resource efficiency as well.

References

[1] T. Kim and I. Bang, "Random access parallelization based on preamble diversity for cellular IoT networks," *IEEE Commun. Lett.*, vol. 24, no. 1, pp. 188-192, Jan. 2020.

[2] H. Jin, W. T. Toor, B. C. Jung, and J. Seo, "Recursive pseudo-bayesian access class barring for M2M communications in LTE systems," *IEEE Trans. Veh. Technol.*, vol. 66, no. 9, pp. 8595-8599, Sep. 2017.

[3] T. Kim, B. C. Jung, and D. K. Sung, "An enhanced random access with distributed pilot orthogonalization for cellular iot networks," *IEEE Trans. Veh. Technol.*, vol. 69, no. 1, pp. 1152-1156, Jan. 2020.

[4] *Evolved universal terrestrial radio access network(E-UTRAN); medium access control (MAC) protocol specification*, 3GPP TS 36.321 V12.7.0, Sep. 2015.