Delay-Aware Dynamic Barring Scheme for Massive Access in NB-IoT Network

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Abstract. In Internet of Things (IoT), narrow band IoT (NB-IoT) based on cellular networks is expected to play an important role for providing low power, wide area services, supporting deep indoor deployment, massive devices in one cell. However, massive access requests in resource-finite situation may bring out severe congestion and delay. To alleviate congestion and delay problems, we propose a delay-aware dynamic barring scheme in this paper. According to different delay requirements, the proposed scheme can ensure higher priority for delay-sensitive services. Compared with standard access class barring (ACB) scheme, both success probability and delay for delay-sensitive devices can be improved significantly, with several sacrifice on delay-tolerant performance.

Keywords: NB-IoT · Massive access · Delay-aware · Dynamic ACB

1 Introduction

With the development of IoT, lower power wide area (LPWA) network attracts more and more attention. The current typical LPWA technologies, for example, Lora and Sigfox, are fragmented and non-standardized, which may bring security issues. For the standardization of the LPWA market, 3GPP proposed NB-IoT based on cellular network, making some simplification both on physical and network layers [1,2]. As a reliable technology, NB-IoT can serve at least 50 thousand modules per cell [3]. With this huge load, legacy access control methods may be not efficient to handle radio access network (RAN) and core network (CN) overload, then heavy congestion and severe delay may incur [4].

In NB-IoT network, random access step must be performed first, by sending preambles in narrow band random access channel (NPRACH) for uplink synchronization. However, if more than one device select one same preamble simultaneously, then collision would be caused, which further caused access congestion. With great potential to generate huge access traffic from numerous devices, collision probability is high, causing serious RAN congestion and long delay.

C. Li and S. Mao (Eds.): WiCON 2017, LNICST 230, pp. 160–170, 2018.
https://doi.org/10.1007/978-3-319-90802-1_14

To alleviate congestion and delay problems, many effective schemes have been proposed in machine-to-machine (M2M) communications [5–8]. 3GPP adopt the proposals of ACB and enhanced ACB mechanism named extended access barring (EAB) in cellular network, which is effective for RAN overload control by allowing a portion of devices to access the channel. If requests far exceeds the access channel capacity, the effect of a single barring scheme will be not obvious, thus [9] proposed a two-layer scheme combining ACB and EAB to enhance the barring performance. A cooperative ACB method is also proposed in [10], with the cooperation of base stations, the access delays can be significantly improved. Unlike the methods towards the decreasing access arrivals, in [11], another grouping scheme to reuse preambles in different groups is proposed, which may cause preamble interference between groups. Generally, the network status depends on arrivals and usable preambles in current slots, thus avoiding the access requests concurrency or exploiting preambles are the two main solutions.

In this paper, we propose an effective way to restrict preamble competitors according to different delay demands. First, a delay threshold should be set according to the acceptable delay tolerance for delay-sensitive devices, then we split devices into two sets by the threshold. Secondly, set a fixed access parameter for the delay sensitive terminals, while each delay tolerant terminal generating a random access parameter. The barring factor is also adaptive about current traffic. Without external resources, our scheme can make sure the delay-sensitive devices have priority to acquire preambles. Results show that the performance of delay-sensitive devices can be improved effectively.

2 Background and System Model

2.1 NPRACH Resource Configuration

As a clean-slate technology, NB-IoT can extend the maximum coupling loss (MCL) 20 dB more than GPRS, then NB-IoT devices can keep working in poor situation with MCL up to 164 dB. In 3GPP proposals, devices based on NB-IoT technology can be divided into 3 categories depending on MCL, called CE0, CE1, CE2 (CE, Coverage Extended), respectively supporting MCL less than 144 dB, between 144 dB and 154 dB, and MCL up to 164 dB. For supporting

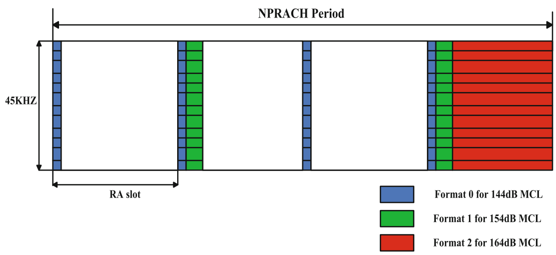

Fig. 1. NPRACH resource configuration.

extended coverage, different categories own different resource configuration. The worst condition, usually refer to basements or other places with poor channel condition, i.e., CE2 scenario, configures the longest preambles in time domain to make sure that requests can be detected by BS. The configuration can refer to Fig. 1.

Obviously, long preambles consume the uplink resources extremely, thus the number of long preambles are limited. In case of average access requests among three categories, devices in CE2 may face the most serious conflicts. In this paper, we analyze proposed schemes on CE2 devices, which is also suitable for the other two situations.

2.2 Access Barring Scheme

To resolve congestion, ACB scheme has been adopted. In each access slot, active devices need to pass through the barring process before sending preambles to BS. The barring factor δ is broadcast by BS. Each active device generates a random p (i.e., access parameter) between 0 and 1. Only if p is less than δ can the corresponding device pass the barrier. Literally, δ determines the expected percentage of active terminals which can apply for preambles. Those devices blocked by barring will be barred for a certain period called barring time, which is also broadcast by BS. The main work is shown in Fig. 2.

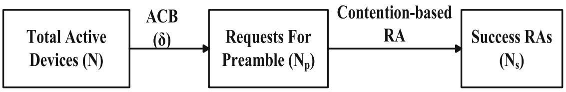

Fig. 2. Access barring scheme.

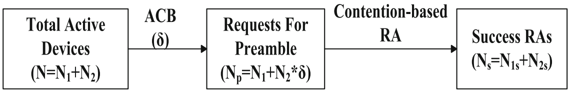

Fig. 3. Delay-aware barring scheme.

2.3 System Model

To avoid weakness on real-time service, devices supported by NB-IoT should allow a certain degree of delay. Thus, terminals with rigor delay limit will not be involved in our study. Under this premise, we present our model.

Generally most devices accept a more tolerant delay, however, the degree of acceptance are quite different among NB-IoT terminals. In rare cases, some applications which are also relatively delay-sensitive, such as alarms in poor environments, have to adopt NB-IoT due to bad channel situation. With low proportion of entire business, although, this part is extremely important. In order to protect the efficiency of these applications, according to delay requirements, we divide all terminals into two categories and propose an access strategy.

Our target is to make sure delay-sensitive devices can pass the barring scheme with a high priority. Only several modules need a shorter delay, thus we can set a time threshold to classify devices. The threshold can be the maximum acceptable delay for delay sensitive scenarios. According to the delay requirements distribution, we split all devices into two classes, called class A and class B. Devices in class A should finish the access within the given time threshold, while others in class B can be more tolerant. In terms of quantity, devices in class A are far less than those in class B.

To ensure the priority of delay-sensitive ones, we change the way access parameter generated. Unlike the original ACB schemes with fair access parameter generation, in our work, set devices in class A with a fixed p_A equal to zero, while devices in class B need to generate random number p_B between 0 and 1. In this model, the whole period we considered, T, is divided into slots indexed by non-negative integer i ($i = 1, 2, \ldots, L$). Then, the access parameters can be described by

$$\begin{cases} p_A(i) \equiv 0, \\ p_B(i) \in (0, 1). \end{cases} \tag{1}$$

No matter how much δ is equal, those belong to class A can always break through the barrier, while part of devices in class B will be banned.

3 Delay-Aware Access Barring Scheme

3.1 Dynamic Barring Factor

To improve access success rate, we change the way barring factor generated. Preambles can be configured in advance, for analysis, assume number of preambles is K and current requests for preambles is m. If more than one select a certain preamble, then all the requests on the preamble can't be detected by BS. The collision probability can be calculated by $p_c = 1 - (1 - \frac{1}{K})^{m-1}$. According to p_c, we set a threshold about the average success requests so as to perform our following scheme. Set $M = \max\{\lceil \hat{m} \rfloor\}$, while $[1 - (1 - \frac{1}{K})^{\hat{m}-1}] < 0.1$, and $\lceil \hat{m} \rfloor$ means the closest integer near $\hat{m}$. Absolutely, more than one value can satisfy the limit of $[1 - (1 - \frac{1}{K})^{\hat{m}-1}] < 0.1$, and M is the maximum of all. The limit less than 0.1 try to make sure at this time $\hat{m}$ devices could complete the random access with 90% probability.

In following analysis, M is regarded as a threshold for adjusting barring factor. Next work is to restrict the active devices around M by designing suitable barring factor. Assume that n and n_1 denote the total active devices and class A devices, respectively, and δ is the dynamic barring factor, then let

$$\delta = \begin{cases} 1 & n \leq M \\ \frac{M - n_1}{n - n_1} & n > M > n_1 \\ 0 & n \geq n_1 > M \end{cases} \tag{2}$$

where δ can limit the preamble requests around M, ensuring success rate of access around 90%.

3.2 Adaptive Random Access Procedure

Based on our work, an adaptive random access strategy is achieved. Assume N is the number of active devices. If N is less than M, $\delta = 1$, then all the active ones can select preambles directly. If N is more than M, according to Eq. (2), each device compare their p_A or p_B with δ. Since $p_A \equiv 0$, devices in class A can always choose preambles directly, however, others in class B will be restricted by δ to some extent. Only if p_B no more than δ can the relative one pass the barrier. If the number of active A-class ones, i.e., N_1, is more than M, only these A devices can pass the barrier, while the lowest δ, i.e., 0, can block all the B-class requests. With extreme less devices in class A, the rate of initiating an access request is low, so the access resources will not be blocked by class A. The dynamic barring scheme can be described by Fig. 3.

4 Performance Analysis and Evaluation

4.1 Arrivals Distribution Model

Unlike human communications, in event-driven business, arrivals no longer satisfies the poisson distribution. Due to large-scale event-driven alarms or paging messages, lots of terminals may need to access simultaneously. As described in [12,13], this business can be modeled as beta distribution. Arrivals in a period of time, denoted as T, with probability $p(t)$, following a beta distribution

$$p(t) = \frac{t^{\alpha-1}T - t^{\beta-1}}{T^{\alpha+\beta-1}Beta(\alpha, \beta)}, \tag{3}$$

with $\alpha = 3$, $\beta = 4$, which is closest to actual situation. $Beta(\alpha, \beta)$ denotes beta function, which is only related to α and β. T can be divided into L slots evenly with τ seconds per slot.

Assume N devices need to communicate with BS in L slots. Then arrivals in each slot can be calculated by

$$N(i) = N \int_{t_{i-1}}^{t_i} p(t)dt, i = 1, 2, \ldots, L. \tag{4}$$

4.2 Performance Analysis

Some measure metrics are proposed for performance analysis. To make contrasts, we also consider the static ACB scheme with fixed barring factor η, where all the devices generate random number between 0 and 1 fairly.

Access Success Probability. Access success probability is defined as the ratio of the successful number $N_s(i)$ to total active devices $N(i)$ in continuous L slots. Thus, average success probability is calculated by

$$p_s = \frac{1}{L}\sum_{i=1}^{L}\frac{N_s(i)}{N(i)} = \frac{1}{L}\sum_{i=1}^{L} p_s(i), i = 1, 2, \ldots, L. \tag{5}$$

In original ACB scheme, with barring factor η, total k preambles available in current configuration, the success probability is calculated by

$$p_s^{ACB}(i) = (1 - \frac{1}{k})^{N(i)\cdot\eta - 1}, i = 1, 2, \ldots, L. \tag{6}$$

In our model, devices in class A and class B follow quite different access parameter patterns, thus, with different probability calculations. Define N_{1i}, N_{2i} as the active number for class A and class B devices in i-th slot. Then the success probability for class A is

$$p_s^{(A)}(i) = \begin{cases} 1 & N_{1i} = 0 \\ (1 - \frac{1}{k})^{N_{1i} - 1} & N_{1i} \geq M \\ (1 - \frac{1}{k})^{N_p(i) - 1} & 0 < N_{1i} < M \end{cases} \tag{7}$$

and for class B,

$$p_s^{(B)}(i) = \begin{cases} 0 & N_{1i} \geq M, N_{2i} \neq 0 \\ (1 - \frac{1}{k})^{N_p(i) - 1} & 0 \leq N_{1i} < M, N_{2i} \neq 0 \\ 1 & N_{2i} = 0, \end{cases} \tag{8}$$

where $N_p(i) = N_{1i} + \delta(i) \cdot N_{2i}$, denoting the requests for preambles.

Access Delay Analysis. In fact, the delay refers to the time from the initiation request to the success of the access. Suppose there are N active devices, average delay is defined as the sum delay of successful numbers divided by the number of successful devices, thus

$$\tau_{avg} = \frac{1}{N}\sum_{j=1}^{N}\tau(j). \tag{9}$$

However, we can't promise all the active devices can access successfully in a certain period. Suppose N_i devices transmit preambles in i-th slot, the total delay is equal to

$$\tau_{tot} = \sum_{i=1}^{L} N_i. \tag{10}$$

The average delay is equal to τ_{tot} divided by the sum of successful accesses denoted as N_s, that is

$$\tau_{avg} = \frac{\tau_{tot}}{N_s}. \tag{11}$$

In our scheme, devices in class A and class B are designed with different barring time, τ for class A, $\lambda \cdot \tau$ ($\lambda > 1$) for class B. The time spent on access is calculated by the next two equations. $\tau_A(i)$ describe the total time consumption in i-th slot by N_{1i} devices while $\tau_{avg}^{(A)}$ means the average delay of $N_s^{(A)}$ class A devices. τ is a fixed time of a slot, a failed A-class device can be barred for τ, just like a new request in following slot. The detailed formula is shown below,

$$\tau_A(i) = N_{1i} \cdot \tau, i = 1, 2, \ldots, L, \tag{12}$$

$$\tau_{avg}^{(A)} = \frac{1}{N_s^{(A)}} \sum_{i=1}^{L} \tau_A(i). \tag{13}$$

For class B, the failed device should be barred for longer time. λ is an integer factor between 1 and 10, which means device should wait for $\lambda \cdot \tau$ when it was banned, with $N_s^{(B)}$ successful requests in T and success probability $p_s^{(B)}(i)$ in i-th slot, having

$$\tau_B(i) = N_{2i} \cdot p_s^{(B)}(i) \cdot \tau + N_{2i} \cdot (1 - p_s^{(B)}(i) \cdot \lambda \cdot \tau, i = 1, 2, \ldots, L, \tag{14}$$

$$\tau_{avg}^{(B)} = \frac{1}{N_s^{(B)}} \sum_{i=1}^{L} \tau_B(i). \tag{15}$$

To make contrasts, the barring time for ACB scheme is equal to τ, and the average delay is calculated by

$$\tau(i) = N_i \cdot \tau, i = 1, 2, \ldots, L, \tag{16}$$

$$\tau_{avg}^{ACB} = \frac{1}{N_s} \sum_{i=1}^{L} \tau_{(i)}. \tag{17}$$

Success Probability in Each Slot for Class A. Using the delay-aware scheme, class A devices own the priority to complete the random access requests. It means that all active devices belong to class A in one slot can possibly complete the access process all at once. Assume N_{2p} devices in class B can pass the barring and select preambles contending with class A, the success probability of first full accesses for class A is calculated by

$$P_o^{(A)}(i) = \begin{cases} \frac{C_{N_{1i}}^k \cdot N_{1i}!}{(k - N_{1i})} & N_{1i} \geq M \\ \frac{C_{N_{1i}}^k \cdot N_{1i}! \cdot (k - N_{1i})^{N_{2p}}}{k^(N_{1i} + N_{2p})} & N_{1i} < M. \end{cases} \quad i = 1, 2, \ldots, L. \tag{18}$$

The equation means, only when N_1 devices choose different preambles from k preambles, at the meanwhile, class B devices choose the other k-N_1 preambles, can make sure all the requests from class A access successfully. To improve readability, the symbols appearing in the text are shown in Table 1.

4.3 Performance Evaluation

To evaluate the performance, we adopt the simulation parameters for NB-IoT devices that have been agreed by 3GPP. Considering $50,000$ devices in a single cell with a uniform distribution geographically. In a predefined period, devices generate access attempts independently. Usually, NPRACH band occupy 180 KHZ, with subcarrier 3.75 KHZ, which means 48 preambles are available per slot. In our analysis, supposing $T = 120\,\mathrm{s}$ as one specified period, let $\tau = 240\,\mathrm{ms}$, i.e., $L = 125$.

For maximizing its advantages of deep coverage, we reasonably assume CE2 terminals occupying the main part of the whole NB-IoT network, for example, half of all. Assume that each terminal randomly initiates an average of 15 access requests per day, thus, approximately 500 access requests are from CE2 in T. To meet the exploded increasing devices in future, we also evaluate the active devices up to $5,000$ per period per cell.

Table 1. Symbols summary.

Symbol	Parameter
N	Total number of active devices
K	Number of preambles per NB-IoT band
M	Maximum requests for preambles satisfying $P_s \geq 0.9$
T	Specified period for one access process
p	Access parameter
δ	Dynamic barring factor
η	Fixed barring factor in ACB
τ	One access slot(240 ms)
P_s	Access success probability
τ_{avg}	Average delay
N_{fail}	Failed devices in T
$P_o^{(A)}$	Success probability for A-class devices

As Fig. 4 shows, when N is less than $1,000$, the ACB with $\eta = 0.4$ works well. However, as N being larger, our scheme performs better than others. With several sacrifice on class B, the success probability of class A is improved effectively, performing well over the fixed ACB scheme with barring factor $\eta = 0.4$ and $\eta = 0.8$.

Figure 5 shows both class A and class B performs well on delay performance. With class A achieving an extreme shorter delay, B-class performs worst when N is less than $4,000$. However, delay of class B is even shorter than class A while N is more than $4,000$. That is because with the active number increasing, less B-class devices can pass the barrier, i.e., $N_s^{(B)}$ is limited, so the average delay seems like better than class A.

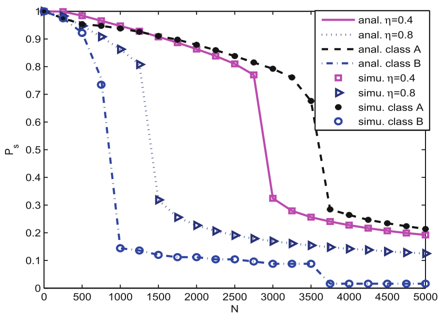

Fig. 4. Access success probability.

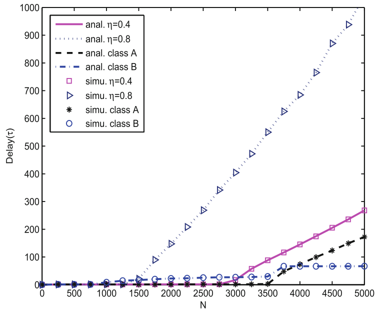

Fig. 5. Access delay for each successful device.

With exponential increasing numbers, not all of the active devices can finish the random access process in our defined period T. Surely, failed requests may continue the access procedure in the following period until finally completed the random access or gave up the packets. We observe the failed numbers and make it as another metric to assess the performance. Failed number is equal to the total active requests minus the successful ones, shown in Fig. 6.

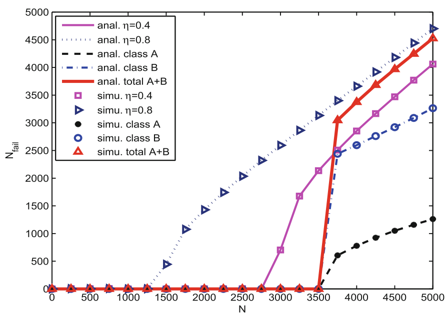

Fig. 6. Failed access numbers at the end of T.

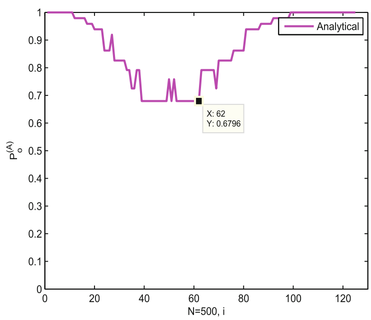

Fig. 7. Success probability of class A in appearance slot.

From the results, we can see the total failed ones, i.e., the sum of failed ones from class A and class B, is always less than the ACB method with $\eta = 0.8$. While N is larger than 3750, total failed numbers are little more than fixed barring $\eta = 0.4$ scheme, however, failed devices in class A is still limited, which mean our proposed scheme perform well on access procedure, guaranteeing priority for handling delay-sensitive requests.

Figure 7 shows the probability of all class devices succeed in apparent slot. Assume the active devices in current period is equal to 500. By protecting the priority of class A to occupy preambles, the probability of all class A requests succeed in first appearance, can be larger than 67%, which is impossible in ACB scheme. Correspondingly, both delay and re-attempts can be limited effectively.

5 Conclusion

In this paper, we have considered the critical issue of NB-IoT communication in 3GPP scenario by proposing the delay-sensitive-protected dynamic barring scheme to improve the congestion and serious delay problems. Simulation results show that the proposed scheme can effectively improve access success probability and reduce access delays for the delay-sensitive services.

Acknowledgements. This work was supported by the National Natural Science Foundation of China (NSFC) under Grants 61427801, 61671251, and 61401224, the Natural Science Foundation Program through Jiangsu Province of China under Grant BK20150852 and BK20140882, and the open research fund of National Mobile Communications Research Laboratory, Southeast University under Grant 2017D05.

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