



A Novel Group Paging Control Method for Massive MTC Accesses in LTE Networks

Cong Wang¹ · Chengqiang Wei² · Ning Li² · Wenfeng Ma¹ · Hui Tian¹

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Abstract

The fifth-generation (5G) systems have to deal with massive deployment of machine-type-communication (MTC) devices. System overload may occur during a random access procedure under a limited number of preamble resources and physical uplink shared channel resources especially when there exist massive MTC devices in a cell. In order to resolve the system overload (caused by the massive MTC deployment), the 3GPP proposed the adopted a group paging (GP)-based uplink access technique. But its performances dramatically decrease as the number of MTC devices increases. In this paper we propose a novel method, named ACB-based group paging overload control method (AGO). To reduce the number of simultaneous access MTC devices, AGO first scatters the MTC devices over a GP interval, and then automatically adjusts ACB parameters according to the load conditions. By doing so, AGO achieves high-channel access probability for MTC devices. Simulation results show that this method is superior to the GP and Pre-backoff mechanisms in terms of success and collision probability, average access latency and resource utilization rate.

Keywords 5G · Group paging · ACB · Massive MTC devices (MTC) · Machine to machine communication (M2M) · Overload control · Random access

Abbreviations

ACB Access class barring

✉ Cong Wang
lgd_dolphin@139.com

Chengqiang Wei
saweichengqiang@sina.com

Ning Li
js_ningli@sina.com

Wenfeng Ma
sat_lab@163.com

Hui Tian
jaytianhui@163.com

¹ College of Field Engineering, Army Engineering University of PLA, Nanjing 210007, China

² College of Communications Engineering, Army Engineering University of PLA, Nanjing 210007, China

GP	Group paging
PBO	Pre-backoff
AGO	ACB-based group paging overload control method
IoT	Internet of thing
MTC	Machine type communication
M2M	Machine to machine communication
LTE	Long term evolution
PUSCH	Physical uplink shared channel
GID	Group ID
RAR	Random access response
RA	Random access
RACH	Random access channel
EAB	Extended access barring
SIB	System information block
RU	Resource utilization
CDF	Cumulative distribution function

1 Introduction

The main goal of Internet of Things (IoT) is to ensure that massive machine type devices access the cellular networks. Machine-type Communication (MTC), also known as machine-to-machine (M2M) communication, is envisioned as a main enabler for the IoT [1]. According to its definition, MTC means the communications between machines (devices) without (or with a little) human intervention [2]. MTC applications have been experiencing rapid growth in various domains, such as intelligent transport systems, smart cities, e-Health, smart grids, industry automation, monitoring and control systems, etc. [3, 4].

Resource allocation for MTC devices is one of the keys challenges in the 5G network [5]. With the development of IoT applications, the number of MTC devices is also growing rapidly. Unlike human-to-human (H2H) communications, in a cellular network, severe network congestion may occur when massive MTC devices initiate random access processes at the same time. Therefore, various methods have been proposed in the existing literature to solve the network congestion problem of the cellular systems. In general, these methods can be divided into two categories: pull-based methods and push-based methods. The access class barring (ACB) scheme and the group paging (GP) scheme are the more representative methods.

Thanks to their ubiquitous coverage, Long-Term Evolution (LTE) networks are considered the most potential enabler for massive Machine-Type Communications (mMTC) service in fifth-generation (5G) context [6]. In LTE networks, GP scheme is an effective mechanism recommended by the 3GPP group to resolve access conflicts. It is a very effective method to control network overload in the pull-based scheme [7]. In the GP scheme, user devices are grouped according to various quality of services (QoS), for example, delay-sensitive devices, delay-tolerant devices, time-controlled devices, mobile devices, fixed devices, etc. Each group is assigned an ID, called Group ID (GID). Therefore, user devices in a group can only be paged by one paging message. When receiving the paging message, all user devices of the group start a random-access procedure in the next available random-access slot at the same time. Since all devices in the same group initiate a

random-access process at the same time, as the number of devices increases, the performance of the GP drops dramatically.

As a congestion control mechanism, ACB has been studied and used in 2G/3G networks [8]. In LTE/LTE-A, the ACB mechanism consists of an AC barring factor and an AC barring time parameter. These two parameters are broadcasted by the Evolved Node B (eNB) to the competing devices (including H2H and M2M) through System Information Block (SIB). Before the device initiates the random-access process, it determines whether the group is prohibited according to the system information. Each device in the forbidden group chooses a random number between 0 and 1, and then compares the random number to the ac barring factor. If it is smaller than the factor, the device starts a random-access process. Otherwise, the device will be forced to enter the back-off process. Thus, MTC devices can achieve high access efficiency in ACB mechanism. However, it is difficult to set ACB parameters according to the load dynamically.

In this paper we propose a novel method, named ACB-based group paging overload control method (AGO). To reduce the number of MTC devices simultaneously initiating a random-access process, AGO first scatters the MTC devices over a GP interval, and then automatically adjusts ac barring factor according to the load conditions.

The remainder of the paper is organized as follows: Sect. 2 gives a brief review of the related works. Section 3 introduces LTE Random Access Procedure. The AGO scheme is elaborated in Sect. 4. The performance evaluation of the AGO scheme is presented in Sect. 5. The paper is concluded in Sect. 6.

2 Relate Works

As massive MTC devices access the network, the problem of network overload becomes more and more serious. According to key problems in recent M2M communications, there are many studies being carried out to alleviate RAN overload and network congestion [9]. These studies divide control mechanism into push-based and pull-based methods [7].

The pull-based mechanisms are central control methods. The network (eNB) initiates the RACH process, and only the paged MTC devices can access the network. As mentioned earlier, among all the pull-based mechanisms, the GP mechanism [7], recommended by the 3GPP, is an effective mechanism for controlling network overload. In the GP mechanism, MTC devices are grouped into different groups, and only devices in the same group can be paged in the one paging message. Many literatures have studied the performance of the GP mechanism. Compared with the method of uniform distributing traffic, in the GP mechanism, all devices in the same group will simultaneously start a random-access process at the first time slot, which will result in an extremely high system load [10]. Therefore, some improvement methods of GP mechanism have been proposed. A method for controlling the random-access process of MTC devices through strict slot scheduling has been proposed in [11]. A consecutive group paging (CGP) to enhance the performance of group paging has been proposed in [12]. However, in some cases, the performance of CGP is worse than the classic GP mechanism. Further, an optimized GP mechanism, named FI-TSFGP, has been proposed in [13]. Compared with the classical GP method, FI-TSFGP scatters the paging operation of the MTC devices over a GP interval. In this way, the FI-TSFGP mechanism has achieved high-channel access probability and reduced energy consumption at the same time. In addition, a method called Pre-backoff (PBO) has been proposed in [14, 15]. In PBO,

some random-access requests are uniformly distributed over a pre-backoff window. PBO scheme can abate the number of MTC devices sending random access requests for a short time and thus can deal with the RAN congestion problem [14]. However, the size of the backoff window has a certain impact on the performance of the system. Then, some scholars started to explore how to set the size of the backoff window. For example, the author in [16] dynamically adjusts the backoff window to ensure that delayed devices do not enter the next paging cycle.

The push-based mechanisms are decentralized radio access network overload control methods. There are the following technologies: ACB mechanism, dynamic resource allocation mechanism and random-access resource separation mechanism, etc.

ACB mechanism is considered as the main solution for M2M communications access control. The existing literatures mainly focus on the dynamic adjustment method of ACB parameters [17–20]. In [17], a dynamic adjustment of ACB parameters with PID has been proposed. In order to adjust ACB parameters, traffic-load needs to be estimated. In reference [18], according to the situation of network collision, a markov-chain based traffic-load estimation scheme has been proposed. Further in [19, 20], two dynamic access class barring (D-ACB) algorithms have been presented. In the paper, these algorithms can adjust the ACB factors dynamical, and effectively improve system performance, such as reducing network delay and total system service time. Different from the centralized method, Reference [21] proposes a distributive optimal ACB parameters estimation algorithm of M2M communications in LTE networks. Compared with the existing centralized methods, the method can achieve similar performance with lower signaling overhead.

Unlike traditional H2H communications, M2M communications service features are different, and the required QoS is also different. To meet different QoS requirements, authors in [22] propose a Multiple Access Class Barring (MACB) mechanism. In MACB, different access priorities are set for different applications. In order to improve access performance, 3GPP has provided the Extended Access Barring (EAB) mechanism. In EAB, the time-delayed MTC devices are divide into 0 to 9 regular access levels. The eNB can enable or restrict the random-access process of MTC devices with a certain access level according to the current overload condition [23]. Reference [24] proposed an EAB mechanism to enhance the performance of ACB scheme. Although the ACB and EAB mechanisms have a certain degree of containment against overload, they still cannot minimize the overload, and EAB mechanisms is mainly for time-tolerant business.

In addition, in order to meet the massive access of MTC devices, researchers have also proposed other methods. For example, reference [25] has proposed a two-stage resource optimization algorithm for H2H/M2M coexistence. The results show that the algorithm can balance the demands of M2M and H2H traffic, and meet their diverse QoS requirements. Reference [26] has proposed two typical methods, one is collision avoidance (CA) method at the user side, and the other is collision resolution (CR) method at the base station (BS) side. Since M2M devices are uplink-centric, reference [27] has proposed an uplink channel resource optimization method using single carrier frequency division multiple access in LTE network.

Both ACB and GP mechanism have disadvantages. As a push-based method, ACB is a decentralized approach, so, the overall resource utilization of the system is not stable. In addition, how to dynamically adjust ACB parameters according to load changes has always been a major problem. GP mechanism, as a pull-based methods, is a centralized control solution, and the overall resource utilization is stable. But GP method has some defects in signaling overhead and inflexibility. In addition, the ACB and GP mechanisms do not perform well in dealing with massive MTC device access.

3 LTE Random Access Procedure

In the LTE system, the user device can only perform data transmission after it has synchronized with the uplink of the system through a random-access process. Random access in LTE is divided into two forms: contention-based random access and contention-free random-access. This paper only studies contention-based random-access methods. The random-access process in LTE system is shown in Fig. 1.

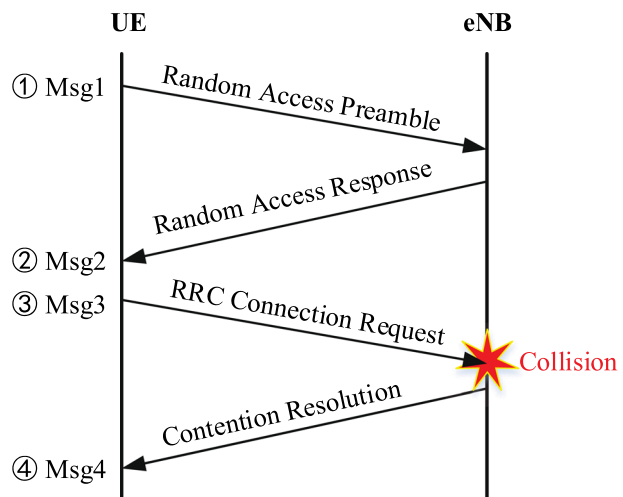
Random Access Preamble Transmission (Msg1): When a device starts an access request to the RACH, it will randomly select a preamble, and transmit the preamble to the eNB via PRACH. Since the preamble selection is randomly, if there are two or more devices selecting the same preamble, and these devices transmit the preamble to the eNB at the same time slot, then there will be a conflict.

Random Access Response (Msg2): After receiving the Msg1, eNB decodes the message, and transmit a RAR response message to the UE devices. The message includes a RA preamble identifier (ID), an uplink grant for MSG3, timing alignment (TA) command for corresponding UEs, and assignment of a temporary identifier (the cell radio network temporary identifier, CRNTI). UEs expect to receive RAR messages within a certain time. If a device doesn't receive RAR message during the certain time, the back-off mechanism will be activated in the back-off window (W_{BO}).

RRC Connection Request (Msg3): When the UE receives the RAR response message, it will send a connection request message with the assigned resource block (RB) on PUSCH to the eNB. The devices, with a preamble conflict in step 1, are configured the same RBs. So, the eNB cannot decode the message of these devices. This will cause the random-access process to fail.

Contention resolution (Msg4): The eNB receives the RRC connection request message. If the eNB can decode the message successfully, it will transmit a contention resolution message to the related devices. If a device receives the contention resolution message, it means that the random-access procedure was successful. Otherwise, it will perform a fallback operation, and launch a new access request later.

Fig. 1 Random access process



4 ACB Based Group Paging Overload Control Method (AGO)

4.1 System Model

We consider a single cell LTE network consisting of a single eNB and a number of MTC devices (M). We assume that these devices are divided into N groups, and are uniformly distributed over the groups. Therefore, there are (M/N) MTC devices in a group. The system model is showed in Fig. 2. The eNB reserves R channel resources for contention-based random-access. In this way, the total available resources for contention-based random-access are equal to the number of frequency bands in a random-access slot multiplied by the number of preambles. For the sake of analysis, we assume that there is only one available frequency band in each random time slot. Therefore, the total available random-access resources are equal to the number of available preambles.

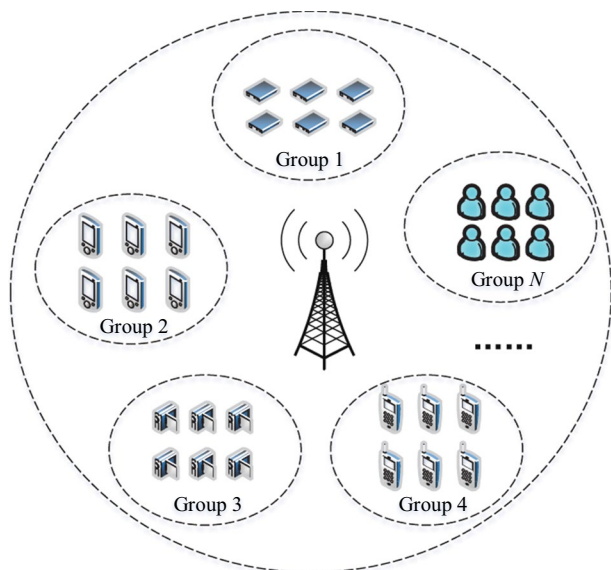
In classical GP method, when the devices in the GID group receive the paging message, which is addressed by the GID, they will initiate the random-access quest at the same time. Different from the classic GP method, AGO combines the ACB mechanism and GP mechanism, and performs ACB mechanism in the paged group. Only those devices that pass ACB detection can initiate a contention-based random-access procedure.

4.2 Group Paging Mechanism

In the LTE system, time is divided into fixed-length radio frames. As shown in Fig. 3, there are several radio subframes in each radio frame. Random-access slot refers to the radio subframe (one or more) used by the devices to complete the random-access process.

In the initial state, after receiving the paging message, the MTC devices in the corresponding group will send the 1st preambles in the first random access slot. If the MTC device competition failed, they will perform a fallback process, wait for a period of time,

Fig. 2 System model



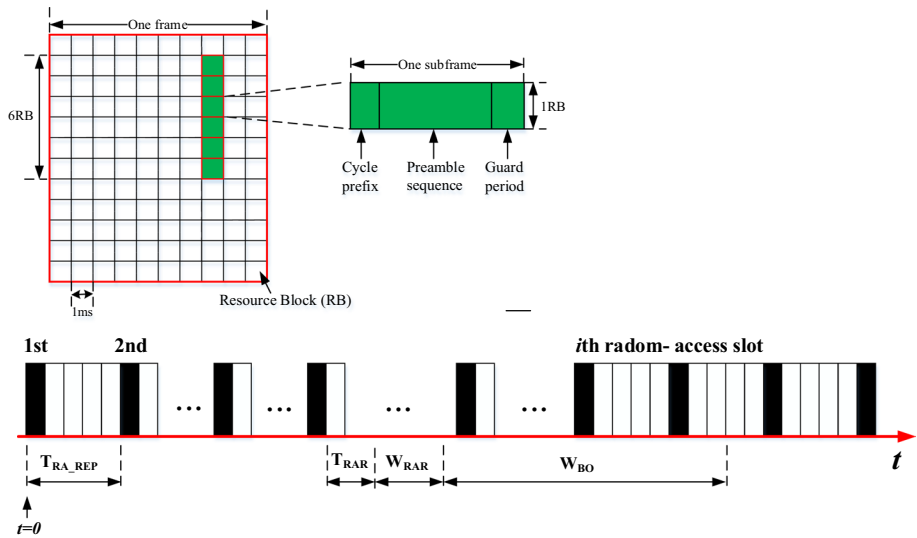


Fig. 3 Random access time slot and resource allocation

and then initiate a random-access request again. We assume that $N_{PT_{\max}}$ represents the maximum number of times the device can retransmit preambles during the paging interval. Then the device re-initiates a random-access request until it successfully accesses or the number of retransmissions reaches $(N_{PT_{\max}} - 1)$ times. For the convenience of discussion, we define the following symbols: T_{RAR} represents the processing delay of the base station, T_{RA_REP} represents the interval between two consecutive RA slots, W_{BO} represents the size of the backoff window, W_{RAR} represents the number of random-access response messages (RAR) contained in the random-access response window, and N_{RAR} represents the maximum number of RARs per a response message.

After sending the Msg1(Random Access Preamble Transmission Message), the MTC device waits to receive RAR message within $T_{RAR} + W_{RAR}$ subframes. We can get the number of RARs included in the RA window as follows:

$$N_{ACK} = N_{RAR} \times W_{RAR} \quad (1)$$

During each preamble transmission, MTC devices need to wait for $(T_{RAR} + W_{RAR} + W_{BO})$ radio subframes before resending a new preamble. We can get the maximum number of RA slots for group paging (I_{\max}) [28]:

$$I_{\max} = 1 + (N_{PT_{\max}} - 1) \left\lceil \frac{T_{RAR} + W_{RAR} + W_{BO}}{T_{RA_REP}} \right\rceil \quad (2)$$

Let R represents the number of preambles reserved by the eNB in each RA slot and p_1 be the detection probability for the first preamble transmission. Then the number of MTC devices that have successfully transmitted the 1st preamble in RA slot is equal to:

$$M_s = M e^{-\frac{M}{R}} p_1 \quad (3)$$

where M represents the total number of MTC devices that will transmit the 1st preamble. If the device fails to transmit the preamble, it will back off for a certain time and then send the preamble again until it reaches the maximum number of retransmissions. Let p_n be the detection probability for the n th preamble transmission. And then we can get the number of MTC devices that have successfully transmitted the n th preamble in RA slot:

$$M_s[n] = M[n]e^{-\frac{M[n]}{R}p_n} \quad (4)$$

where $M[n]$ represents the total number of MTC devices that will transmit the n th preamble and $p_n = 1 - e^{-n}$.

Since we divide the paging interval into I_{\max} different RA time slots. In this way, at each RA slot, the number of devices that initiate access requests is equal to the total number of devices that send n th preambles. Here n is equal to 1, 2, 3, ..., $N_{PT_{\max}}$.

M_i represents the number of MTC devices that started the RA procedure in the i slot. $M_i[n]$ represents the number of MTC devices that transmitted the preamble for the n th times in the i th slot. $M_{i,s}[n]$ is the number of devices that successfully transmitted the preamble for the n th times in slot(i). $M_{i,c}[n]$ is the number of devices that failed to transmit the preamble for the n th times in slot(i). The number of successful MTC devices is equal to [28]:

$$M_{i,s}[n] = \begin{cases} M_i[n]e^{-\frac{M_i}{R}p_n}, & \text{if } M_{i,s} \leq N_{ACK} \\ \frac{M_i[n]e^{-\frac{M_i}{R}p_n}}{M_{i,s}}N_{ACK}, & \text{otherwise} \end{cases} \quad (5)$$

$$\begin{aligned} M_{i,c}[n] &= M_i[n] - M_{i,s}[n] \\ &= \begin{cases} M_i[n](1 - e^{-\frac{M_i}{R}p_n}), & \text{if } M_{i,s} \leq N_{ACK} \\ M_i[n](1 - \frac{p_n}{M_{i,s}})N_{ACK}, & \text{otherwise} \end{cases} \end{aligned} \quad (6)$$

Let $M_{i,s}$ be the number of MTC devices that have successfully transmitted the preamble and finished the contention-based RACH procedure at RA slot(i). It can be defined as follows.

$$M_{i,s} = \sum_{n=1}^{N_{PT_{\max}}} M_i[n]e^{-\frac{M_i}{R}p_n} \quad (7)$$

Then, M_i can be derived by the following equation [29]:

$$M_i = \sum_{n=1}^{N_{PT_{\max}}} M_i[n] \quad (8)$$

4.3 ACB Mechanism

If there are a large number of devices waiting for access in RA time slot(i), access conflicts will still be caused, resulting in network performance degradation. In order to reduce the collision probability, AGO dynamically adjusts the ACB parameters according to the amount of loading in each RA slot.

AC barring factor is the most important parameter in the ACB mechanism. It is a number between 0 and 1, indicating the probability of forbidden access to the network. If an MTC device belongs to a forbidden group, its ability to initiate a random-access process depends on the ac barring factor. The device randomly selects a value between $[0,1]$ and compares it with the value of ac barring factor. If the value is less than the factor, the MTC device can initiate the random-access process, otherwise it is barred [30].

Let $P(M_{i,s} = m | M_i = n)$ be the probability of m devices successfully completing the random access process, while n devices attempt to access the network. The probability P consists of two parts:

- Probability of k out of n devices passing through ACB mechanism, $P(M_{ACB}^i = k | M_i = n)$.
- In the case where k devices pass ACB detection, the probability of m devices completing the random access process, $P(M_{i,s} = m | M_{ACB}^i = k)$.

So, $P(M_{i,s} = m | M_i = n)$ is equal to:

$$P(M_{i,s} = m | M_i = n) = \sum_{k=0}^n P(M_{ACB}^i = k | M_i = n) \times P(M_{i,s} = m | M_{ACB}^i = k) \quad (9)$$

Let p_{acb} be the ac barring factor, and then we can get:

$$P(M_{ACB}^i = k | M_i = n) = \binom{n}{k} p_{acb}^k (1 - p_{acb})^{n-k}, 0 \leq k \leq n \quad (10)$$

Among the R preambles, the probability of each preamble being selected is the same, which is equal to $1/R$. In this case, the probability of any device that completes the random access process is [31]:

$$P(Z_j = 1 | M_{ACB}^i = k) = \binom{k}{1} \frac{1}{R} \left(1 - \frac{1}{R}\right)^{k-1} \quad (11)$$

where Z_j represents the state of the preamble j . $Z_j = 1$ means that the current preamble j is selected by only one device, $Z_j = 0$ means that the current preamble j is not selected, and $Z_j = c$ means that the current preamble j is selected by two or more devices.

So, we can get the expected value of the number of preambles successfully transmitted, and it can be defined as:

$$E(M_{i,s} | M_{ACB}^i = k) = \sum_{j=1}^R \binom{k}{1} \frac{1}{R} \left(1 - \frac{1}{R}\right)^{k-1} \quad (12)$$

Combining formulas 9, 10 and 12, in the random access slot i , when the total number of devices to be accessed is n , the expected value of the number of successfully transmitted preambles is:

$$\begin{aligned}
& E(M_{i,s} | M_i = n) \\
&= \sum_{k=1}^n \binom{n}{k} p_{acb}^k (1 - p_{acb})^{n-k} \binom{k}{1} \left(1 - \frac{1}{R}\right)^{k-1} \\
&= np_{acb} \left(1 - \frac{p_{acb}}{R}\right)^{n-1}
\end{aligned} \tag{13}$$

Therefore, the probability that the preamble selected by any device is successfully transmitted is:

$$P_S = p_{acb} \left(1 - \frac{p_{acb}}{R}\right)^{n-1} \tag{14}$$

Differentiating Eq. 14 with respect to p_{acb} , we can get:

$$\frac{dP_S}{dp_{acb}} = \left(1 - \frac{p_{acb}}{R}\right)^{n-2} \left(1 - \frac{np_{acb}}{R}\right) \tag{15}$$

According to formula 15, we can draw the following conclusions:

- In the case of $R \geq n$, if $p_{acb} = 1$, the maximum access success probability can be obtained.
- In the case of $R < n$, if $p_{acb} = R/n$, we can get the maximum access success probability.

In summary, we can know that the optimal ac barring factor is [32]:

$$p_{acb}^* = \min\left(1, \frac{R}{M_i}\right) \tag{16}$$

When the random-access process occurs, the eNB calculates the optimal ac barring factor according to the network load in the current time slot. As the author did in the reference [33], we can use the idle or the collision preambles to estimate network load. Devices attempting to access the eNB randomly select a value between [0,1] and compare it with the ac barring factor. Only devices with random number less than the value of ACB parameter may be allowed to participate in the random-access process. Devices that fail the ACB test will start the back-off mechanism and wait for the next access opportunity.

Finally, the number of competing devices in each random-access slot can be dynamically controlled by Eq. 17.

$$M_i = \sum_{n=1}^{N_{PT_{\max}}} (M_i[n] \times p_{acb}^*) \tag{17}$$

4.4 Analytical Model

In this section, we will use an analytical model [13] to analyze the performance of the AGO.

At the first available RA slot, the devices, which are paged, will send the preamble. Due to the limited number of preamble resources and physical uplink shared channel (PUSCH)

resources, some device will be collided. Through the previous analysis, we know that the number of devices that send the preamble for the first time in each RA slot should be equal to the number of newly arrived devices, for example, $M_i[1] = M_{arv}$. Then after the first time slot is completed, the number of successfully connected and failed devices are [13]:

$$M_{1,s} = \begin{cases} M_i e^{-\frac{M_i}{R} p_1}, & \text{if } M_i e^{-\frac{M_i}{R} p_1} \leq N_{ACK} \\ N_{ACK}, & \text{otherwise} \end{cases} \quad (18)$$

$$M_{1,c} = M_1 - M_{1,s} \quad (19)$$

After the RAR window, the device that fails to transmit the preamble at the first time will go back for a certain time and restart the random-access process. Since the back-off time is uniformly distributed, the collided devices are uniformly distributed over the back-off window. The number of devices that transmit the preamble at the second time in a RA slot is equal to the part of slots (named as ∂_a , ∂_{bc} and ∂_d), from the back-off interval, falling before this RA slot multiplied by the number of collided MTC devices. The position of the first RA slot (a) in the back-off window is shown in Fig. 4. The figure shows that the first preamble transmission process and the devices that failed to access the eNB follow the back-off mechanism and wait for the second preamble transmission. From the figure, the position of the first RA slot (a) in the back-off window is as follows [13]:

$$x_a(i) = i + \left\lceil \frac{T_{RAR} + W_{RAR}}{T_{RA_REP}} \right\rceil \quad (20)$$

where, $x_a(i)$ is the order of the first RA slot in the back-off window. The proportion of the MTC devices for the second preamble transmission in time slot (a) is equal to the time of

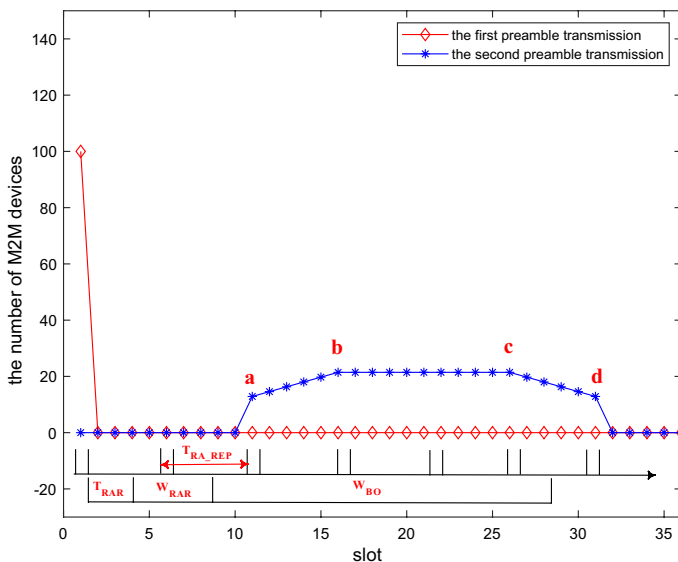


Fig. 4 Number of MTC devices at each RA slot for the first and second preamble transmission for $R = 54$ and $M/N = 100$ [13]

the slot (a), in a subframe unit, minus the duration before the start of the back-off window (normalized by W_{BO}):

$$\partial_a = \frac{\left\lceil \frac{T_{RAR} + W_{RAR}}{T_{RA_REP}} \right\rceil T_{RA_REP} - (T_{RAR} + W_{RAR})}{W_{BO}} \quad (21)$$

Regarding the RA slots from (b) to (c), they will be just after the RA slot(a), i.e.:

$$x_{bc}(i) = i + \left\lceil \frac{T_{RAR} + W_{RAR}}{T_{RA_REP}} \right\rceil + h \quad (22)$$

where, $h = 1, 2, \dots, H_{\max}$. H_{\max} represents the number of RA slots between the slots (b) and (c). It is equal to $H_{\max} = \lfloor (W_{BO} - \partial_a W_{BO}) / T_{RA_REP} \rfloor$. However, the proportion of MTC devices that retransmit their preambles at these RA slots is equal to:

$$\partial_{bc} = \frac{T_{RA_REP}}{W_{BO}} \quad (23)$$

The remaining devices will be retransmitted in the RA slot (d), then the position of RA slot (d):

$$x_d(i) = i + \left\lceil \frac{T_{RAR} + W_{RAR} + W_{BO}}{T_{RA_REP}} \right\rceil + 1 \quad (24)$$

The proportion of devices that retransmit in RA slot (d):

$$\begin{aligned} \partial_d &= 1 - \partial_a - \partial_{bc} H_{\max} \\ &= \frac{T_{RAR} + W_{RAR} + W_{BO}}{W_{BO}} \\ &\quad - \frac{T_{RA_REP}}{W_{BO}} \left\lceil \frac{T_{RAR} + W_{RAR} + W_{BO}}{T_{RA_REP}} \right\rceil \end{aligned} \quad (25)$$

Since more than N_{ACK} devices cannot get network services, formula 5 can be rewritten as:

$$M_{i,s}[n] = M_i[n] e^{-\frac{M_i}{R} p_n} \quad (26)$$

Therefore, we can get the following results:

$$M_{i,s}[1] = M_i[1] e^{-\frac{M_i}{R} p_1} \quad (27)$$

$$M_{i,c}[1] = M_i[1] - M_{i,s}[1] = M_i[1](1 - e^{-\frac{M_i}{R} p_1}) \quad (28)$$

According to Eq. 8, when $t = 1$, we have:

$$M_1 = \sum_{n=1}^{N_{PT_{\max}}} M_1[n] \quad (29)$$

It is easy to get from Fig. 4:

$$\begin{aligned}
M_1[1] &= M_{arv} \\
M_1[2] &= M_1[3] = \dots = M_1[N_{PT_{\max}}] = 0 \\
M_1 &= M_{arv} \\
M_{1,c}[1] &= M_1[1](1 - e^{-\frac{M_1}{R} p_1})
\end{aligned} \tag{30}$$

Similarly, we can get M_2 , and $M_2 = M_{arv}$.

Continually, when $t = 3$, we can get:

$$M_3 = \sum_{n=1}^{N_{PT_{\max}}} M_3[n] \tag{31}$$

$$\begin{aligned}
M_3[1] &= M_{arv} \\
M_3[2] &= \partial_a M_{1,c}[1] = \partial_a M_1[1](1 - e^{-\frac{M_1}{R} p_1}) \\
M_3[3] &= M_3[4] = \dots = M_3[N_{PT_{\max}}] = 0 \\
M_3 &= M_{arv} + \partial_a M_1[1](1 - e^{-\frac{M_1}{R} p_1})
\end{aligned} \tag{32}$$

By induction, we can get M_i , for each time slot(i).

In the previous hypothesis, we considered that the newly arrived devices for each time slot is constant, M_{arv} . But in practical systems, in general, the device arrival rate obeys a specific distribution. For the burst massive MTC devices access scenario, we adopt the beta distribution as the MTC arrival model, and its distribution period is I_{\max} . As in reference [34], the parameters of beta distribution are $\alpha = 3$ and $\beta = 4$.

$$g(t) = \frac{t^{\alpha-1}(I_{\max} - t)^{\beta-1}}{I_{\max}^{\alpha+\beta-1} B(\alpha, \beta)} \tag{33}$$

t represents the sequence number of RA slot. $B(\alpha, \beta)$ is the Beta function, and $g(t)$ is the distribution probability of M2M devices at each random access time. Therefore, the number of new arrivals of MTC devices in each random-access slot is $M_{arv}(t)$:

$$M_{arv}(t) = (M/N) \int_t^{t+1} g(t) dt \tag{34}$$

Assuming $M/N = 1000$, The number of total devices, the successful devices and the collision devices for each preamble transmission in each random-access slot are shown in Fig. 5.

The change rule of the ac barring factor and the number of MTC devices under different conditions are shown in Fig. 6. When $M/N = 500$, the number of devices in each time slot is less than the number of preamble available, and then the ACB mechanism does not work, so $M_i[1] = M_{arv}(i)$. When the number of devices in each time slot is greater than the number of preamble available, such as $M/N = 2500$ or $M/N = 5000$, the ACB mechanism begins to work to prevent too many devices from initiating access requests in the same time slot. As shown in the Fig. 6, the number of devices is greatly reduced.

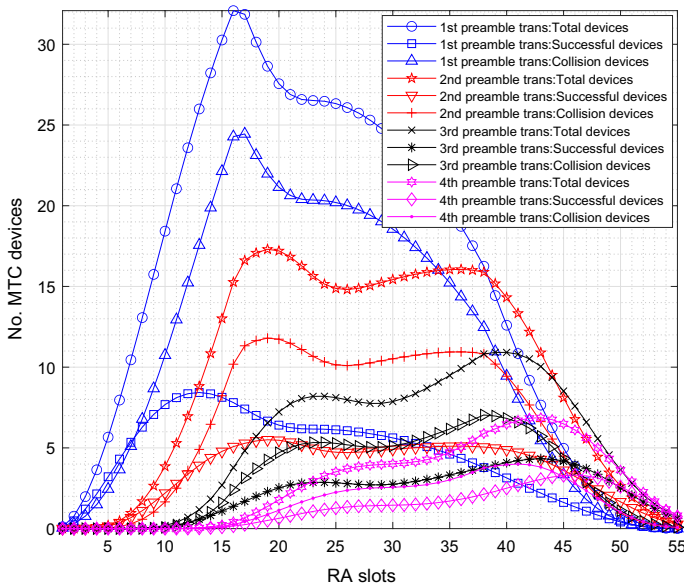


Fig. 5 The number of the total devices, the successful devices and the collision devices for each preamble transmission in each random-access slot; $M/N = 1000$, $P_{T_{\max}} = 10$, $\alpha = 3$, $\beta = 4$

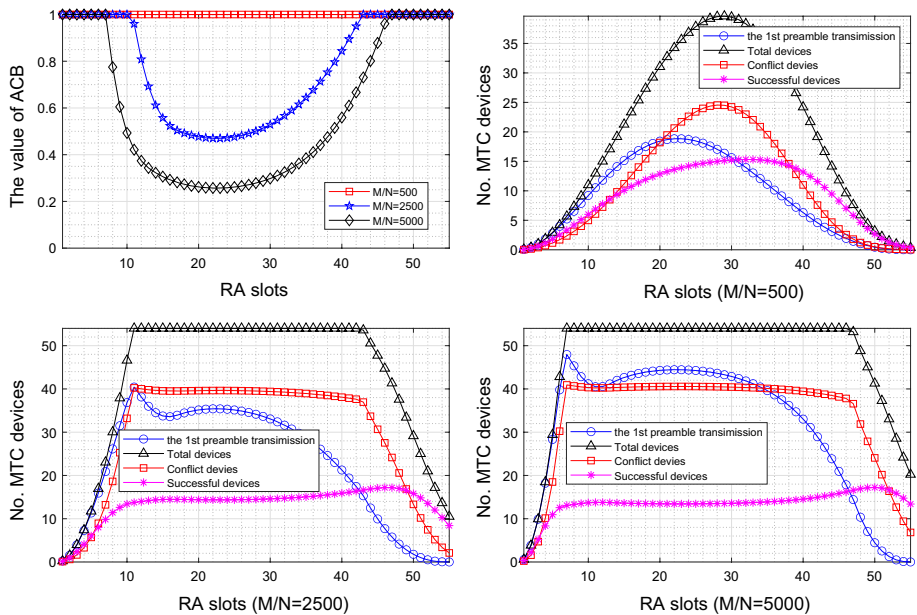


Fig. 6 The value of ac barring factor, and the change rule of the NO. MTC devices under different conditions; $\alpha = 3$, $\beta = 4$, $R = 54$, $W_{BO} = 21$, $T_{RA_REP} = 5$ and $N_{PT_{\max}} = 10$

5 Performance Evaluation

5.1 Performance Metrics

We investigate five performance metrics to evaluate the proposed AGO method: Average access delay, success probability, collision probability, the times of preamble transmission, and resource utilization. In order to show the performance of AGO, AGO will be compared with two classic methods: GP and PBO ($W_{PBO} = 100$ and $W_{PBO} = 240$, respectively). The simulation parameters are shown in Table 1.

A. Average Delay

The Average Delay (\overline{D}_a) represents the average time for the device to finish the random access process successfully. It is equal to the total time delay of the devices that successfully completed the access process divided by the number of devices that completed the access process successfully. T_i represents the time from the device initiating the request to completing the preamble and information transmission in RA slot i . The definition of T_i is as follows [28]:

$$T_i = (i - 1)T_{RA_REP} + (T_{RAR} + W_{RAR}) + \overline{T}_{MSG} \quad (35)$$

\overline{T}_{MSG} represents the average time for the device to successfully transmit information (including message3 and message4). In this paper, we assume that \overline{T}_{MSG} is 11ms, so the average access delay is:

$$\overline{D}_a = \frac{\sum_{i=1}^{I_{\max}} \sum_{n=1}^{N_{PT_{\max}}} M_{i,s}[n] T_i}{\sum_{i=1}^{I_{\max}} \sum_{n=1}^{N_{PT_{\max}}} M_{i,s}[n]} \quad (36)$$

Table 1 Basic simulation parameters

Notations	Definitions	Values
M/N	Total number of MTC devices	10–5000
R	Available preamble resources	54
p_{acb}	AC barring factor	0.1–0.95
$N_{PT_{\max}}$	Maximal times of preamble transmission	10
N_{RAR}	Maximal number of RAR that can be carried in a response message	3
T_{RAR}	The processing delay of the eNB	2
W_{RAR}	Size of the random-access response window	5
N_{ACK}	Maximal number of MTC devices that can be acknowledged within the RAR window	$N_{RAR} \times W_{RAR}$
T_{RA_REP}	Interval between two consecutive random-access slots	5
W_{BO}	Size of back-off window	$BI + 1$
p_n	Detection probability	$p_n = 1 - e^{-n}$
BI	Back-off indicator	20
\overline{T}_{MSG}	The average time for the device to successfully transmit information	11

B. Success Probability

The Success Probability (P_S) refers to the number of devices that complete the entire random access process within the maximum times of preamble transmissions divided by the total number of devices (including devices that are activated or sleep). Its definition is as follows:

$$P_S = \frac{\sum_{i=1}^{I_{\max}} \sum_{n=1}^{N_{PT_{\max}}} M_{i,s}[n]}{M} \quad (37)$$

C. Collision Probability

The Collision Probability (P_C) is the ratio of the number that two or more MTC devices select the same preamble and transmit in the same RB to the total number of preambles reserved by the eNB [23]. In other words, P_C is the ratio of the total number of preambles in conflict to the total number of preambles reserved. In each random access time slot i , the conflicting preambles are equal to the reserved preambles (R) of the eNB minus the successful preambles ($M_i e^{-\frac{M_i}{R}}$) and the idle preambles ($R e^{-\frac{M_i}{R}}$) [35]. Then collision probability P_C is:

$$P_C = \frac{\sum_{i=1}^{I_{\max}} (R - M_i e^{-\frac{M_i}{R}} - R e^{-\frac{M_i}{R}})}{I_{\max} R} \quad (38)$$

D. The Number of Preambles Transmission

Let k indicate the times of preamble transmission by an MTC device from the time it started transmitting an RA request to the time it completed the RA process. Cumulative distribution function (CDF), $F(k)$, is the statistical value of the number of preamble transmissions. $F(k)$ is a ratio, which refers to the ratio of the number of devices that complete the random-access process to the total number of completed random access processes when the number of preamble transmissions is not greater than k . $F(k)$ ranges from 0 to 1. Hence, according to the reference [28], $F(k)$ is expressed as follows:

$$F(k) = \frac{\sum_{i=1}^{I_{\max}} \sum_{m=1}^k M_{i,s}[m]}{\sum_{i=1}^{I_{\max}} \sum_{n=1}^{N_{PT_{\max}}} M_{i,s}[n]} \quad (39)$$

E. Resource Utilization

The Resource Utilization (RU) can be defined as the ratio of the total number of successful MTC devices to the total number of available preambles, and it can be given by the following equation:

$$RU = \frac{\sum_{i=1}^{I_{\max}} \sum_{n=1}^{N_{PT_{\max}}} M_{i,s}[n]}{I_{\max} R} \quad (40)$$

5.2 Numerical Results

Figure 7 shows the average access delay of the three mechanisms, and Fig. 8 shows the CDF of access delay. From the figures, we find that the average access delay of GP grows fastest when the number of devices increases. When the number of MTC devices reaches

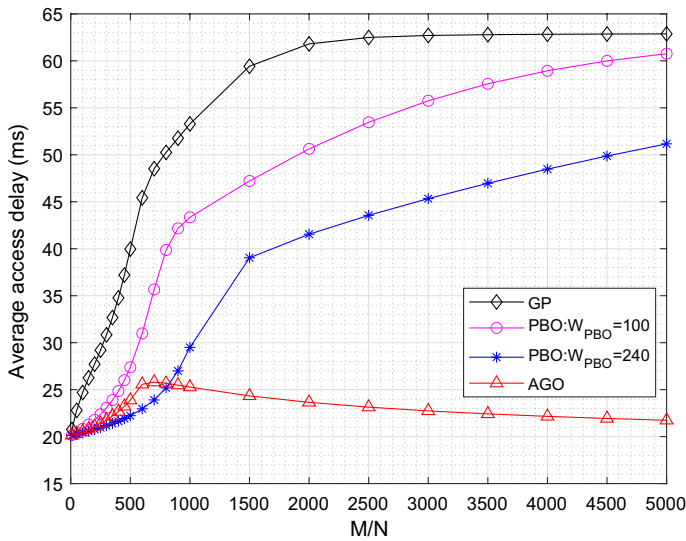


Fig. 7 Average access delay for the considered methods

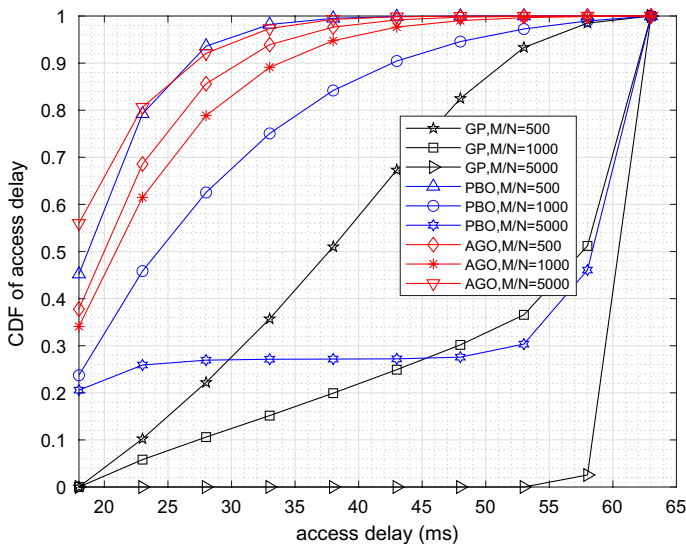


Fig. 8 The CDF of average access delay for the considered methods

2000, the average access delay reaches the maximum (> 60 ms) and remains stable. This shows that, for larger group sizes, the devices in GP may retransmit for $N_{PT_{\max}}$ times to successfully access (Fig. 8). Compared with GP, PBO has an important improvement, and no matter $W_{PBO} = 100$ or $W_{PBO} = 240$, the access delay of PBO is better than GP. Especially when $W_{PBO} = 240$, the access delay of PBO increases slowly when the number of devices increases. When $M/N = 5000$, the average access delay of PBO ($W_{PBO} = 240$) is about 50ms. Compared with GP and PBO, when the number of devices in a group is

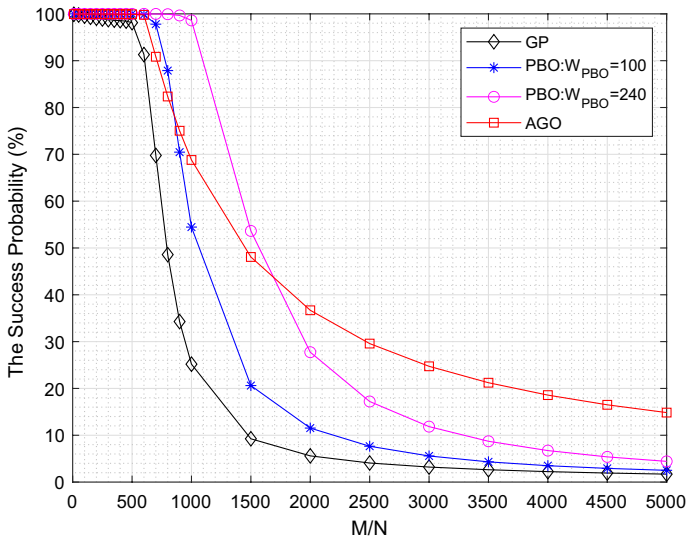


Fig. 9 The success probability for the considered methods

small, the performance of AGO is worse than PBO ($W_{PBO} = 240$), but better than GP and PBO ($W_{PBO} = 100$). As the number of MTC devices in the group increases (when $M/N > 1000$), the performance is significantly better than the GP and PBO. Moreover, the delay is relatively stable and is not affected by the number of devices. For AGO, when $M/N \leq 700$, the access delay increases with the number of devices. However, when $M/N > 700$, the access delay decreases with the increase in the number of devices, and eventually remains stable. This is because when the number of devices is small, the ACB mechanism does not work, so the delay increases as the number of devices increases. When the number of devices is large, the ACB mechanism starts to control the number of devices that access the network at the same time, so the delay will remain stable.

According to the success probability simulation results (Fig. 9), When $M/N \leq 500$, because the available preamble resources are greater than the number of MTC devices waiting to be accessed, the success probabilities of all methods are equal to 100%. When $500 < M/N < 1000$, AGO, GP and PBO ($W_{PBO} = 100$) drop significantly. In comparison, the performance of PBO ($W_{PBO} = 240$) is still relatively good, which can be maintained at about 100%. When $1000 < M/N < 1700$, the performance of all mechanisms drops rapidly. In this case, PBO ($W_{PBO} = 240$) performs better than AGO. When the number of MTC devices is large (e.g., more than 2000), the GP and PBO drop significantly. In contrast, the performance degradation of the AGO is relatively flat. When $M/N = 5000$, the success probability can still be maintained at more than 15%. This means that AGO is more suitable for the scenario of large-scale MTC devices.

As shown in Fig. 10, AGO has effectively alleviated the network congestion problem. As the number of MTC devices increases, the collision probability of AGO increases slightly, but the increase rate is slower. Finally, the collision probability is controlled at about 20%. For the GP and the PBO ($W_{PBO} = 100$), as the number of MTC devices increases, the collision probability increases rapidly. When $M/N = 500$ to 1500, the collision probability increases rapidly from 20% to about 60%. Then the collision probability tends to be stable. When $M/N \geq 4000$, the collision probability is over 70%, and close

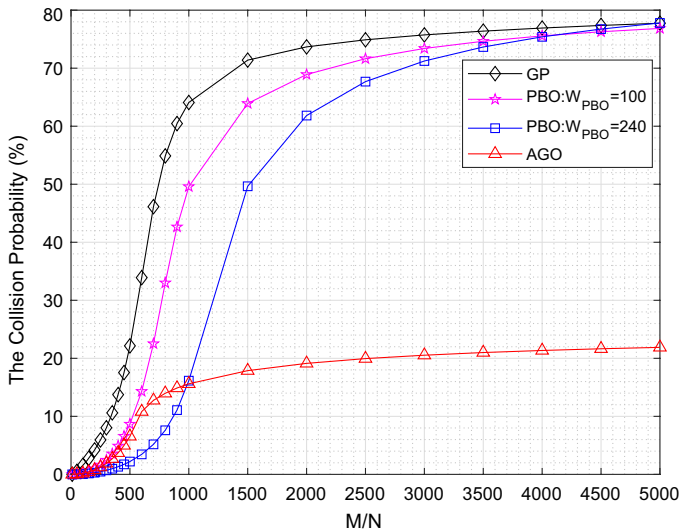


Fig. 10 The collision probabilities for the considered methods

to 80%. PBO ($W_{PBO} = 240$) performs better than GP and PBO ($W_{PBO} = 100$), but when $M/N > 2000$, the collision probability exceeds 70% too. In summary, when the number of MTC devices is large (e.g., more than 3500), the collision probabilities of GP and PBO are close to 80%. However, AGO always controls the collision probability below 30% through the ACB mechanism.

Figure 11 shown the average number of preamble transmission, and Fig. 12 shows the CDF of the preamble transmissions. In general, the performance of PBO ($W_{PBO} = 240$) is better than GP, and the performance of AGO is better than both of them. In GP, in the case of $M/N = 500$, when the number of preamble transmission exceeds 5, the probability of success can reach 50%. And more than 7 times, the probability of success can exceed 80% (Fig. 12). For PBO, in the case of $M/N = 500$, it performs best. But when the number of MTC device is large (e.g., 1000, 5000), its performance drops. Especially when $M/N = 5000$, the average number of preamble transmission exceeds 7. This means that more retransmissions are required to complete the access process. In comparison, AGO has little change in performance when $M/N = 500$ and $M/N = 1000$. When the number of preamble transmissions exceeds 3 times, the success rate of AGO can reach 80% (Fig. 12). When the number of MTC device reach 5000, due to the ACB mechanism, the performance is better than when $M/N = 500$ or 1000. In summary, when the number of devices in the group is consistent, AGO significantly reduces the times of preamble transmissions compared to other methods. From the perspective of energy consumption, our proposed method reduces the number of retransmissions, thereby reducing energy consumption, so it is more conducive to the communication of MTC devices.

As shown in Fig. 13, from the perspective of resource utilization, when the number of MTC devices is relatively small (e.g., $M/N < 700$), the RU rate of GP is better than PBO. When the number of MTC devices is large (e.g., $M/N > 700$), PBO behaves better than GP. For PBO, when the number of MTC devices is small (e.g., $M/N < 1000$), PBO ($W_{PBO} = 100$) achieve a better performance, in contrast, when the number of MTC devices is large (e.g., $M/N > 1000$), PBO ($W_{PBO} = 240$) performs better. Combining the

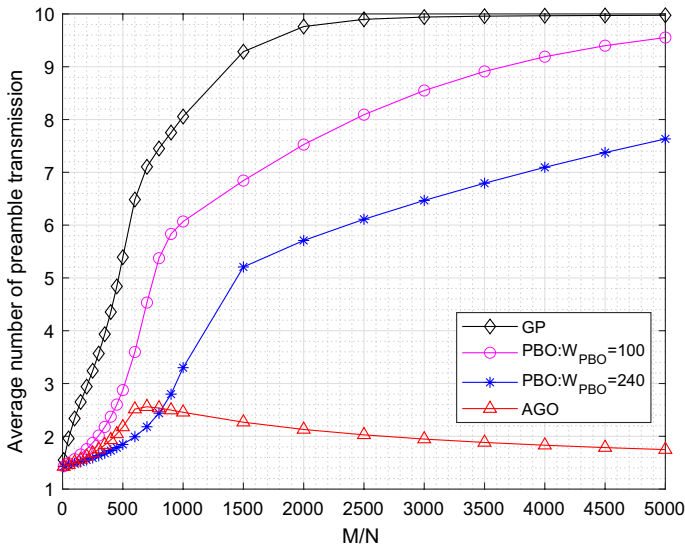


Fig. 11 The average number of preamble transmission for the considered methods

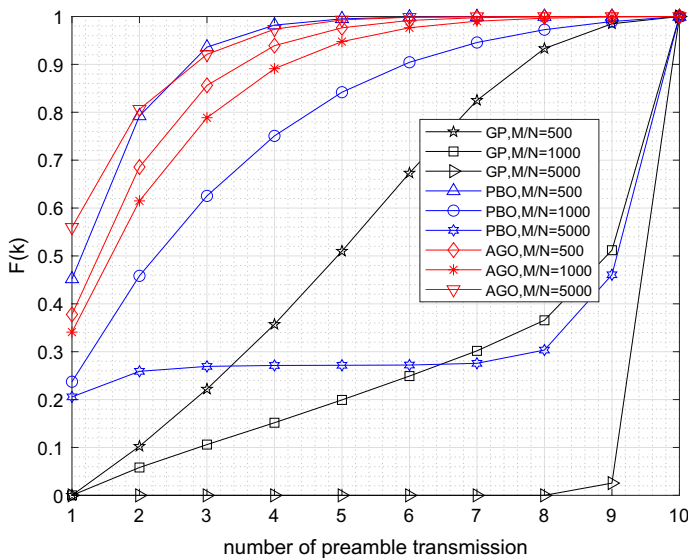


Fig. 12 The CDF of average number of preamble transmissions for the considered methods

previous conclusions, we find that PBO ($W_{PBO} = 240$) performs better in large-scale device scenarios. However, with the increase of MTC devices, the RU decreases significantly, and finally the RU is less than 5%. Compared with GP and PBO, AGO achieves higher RU (when $M/N = 1000$, $RU = 23.16\%$). AGO does not decrease as the number of MTC devices increases, especially when the number of MTC devices is large (e.g., 5000), AGO

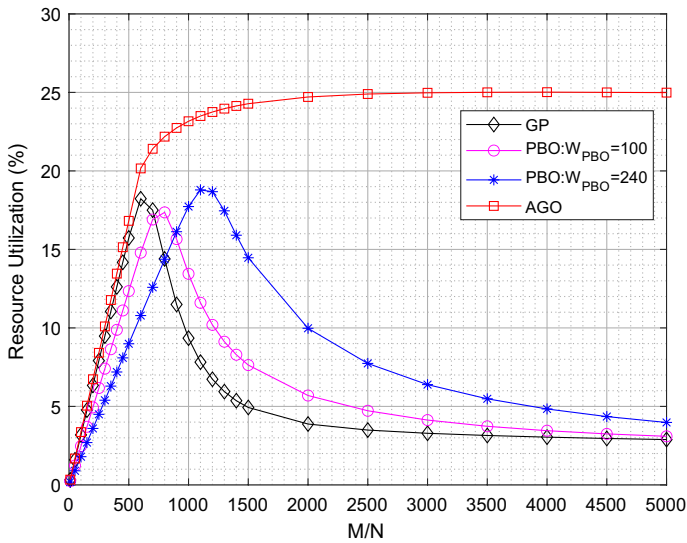


Fig. 13 The resource utilization for the considered methods

remains at about 25%. This shows that the ACB mechanism controls the number of devices well, thereby improving RU.

Figure 14 uses the access success probability as an example to show the impact of different ac barring factors on AGO. As shown in the figure, there are four methods, AGO with the dynamic ac barring factor and AGO with the fixed ac barring factor (0.3, 0.6, 0.9) respectively. When p_{acb} is small (e.g., 0.3 or 0.6), even when there are relatively few MTC devices (e.g., 500), the overall success probability is low because the number of devices that pass the

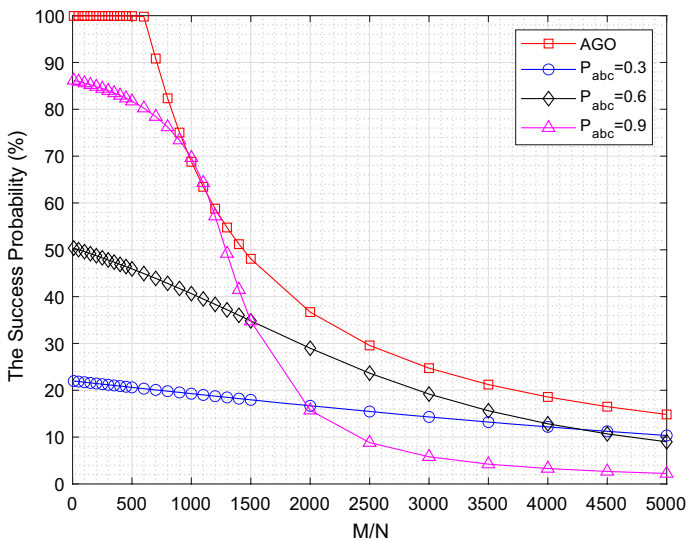


Fig. 14 Comparison of access success probability for different ac barring factor

ACB mechanism is relatively small. When p_{acb} is large (e.g., 0.9), when the number of MTC devices is relatively small (e.g., <1000), the performance is better. However, when the number of MTC devices increases, the performance drops sharply. When $M/N = 5000$, the access success probability drops to between 2% and 3%. AGO, which uses the dynamic ACB parameter adjustment method, achieves the best performance because it can adaptively adjust the parameters according to the access load.

6 Conclusions

In this paper, we have proposed an ACB-based group paging overload control method for massive MTC accesses in LTE network. Instead of all MTC devices in the group can access the random-access process, only MTC devices passed the ACB mechanism can access the random-access process. In this paper, we first scatter the MTC devices over a GP interval reduce access conflicts. And then we assume that the newly arrived MTC devices obey the beta distribution, and calculate the number of newly arrived devices. We calculate the number of devices needed to access the network in the current time slot according to the number of newly arrived devices and the devices in the previous time slot that failed to access. Based on this, AGO can adjust the ACB parameters dynamically. AGO has been evaluated for a relatively large number of MTC devices (5000 MTC devices). Compared with GP and PBO mechanisms, AGO achieves many improvements, in term of success probability, collision probability, resource utilization rate and average access delay, etc. Beside the success probability, average access delay improvements, AGO controls the collision probability very well. When the number of MTC devices is large (5000 MTC devices), the collision probability can also be controlled at about 20%. In addition, AGO also achieved good results in terms of average number of preamble transmissions. Regardless of the number of MTC devices, AGO can achieve a success probability of about 90% under the preamble transmission of about 4 times. This shows that the number of devices in the group has little effect on AGO. Therefore, AGO is more suitable for massive MTC device application scenarios.

Author Contributions WC and WC conceived the idea and wrote the paper; LN analyzed the simulation results; MW and TH performed the experiments. All of the authors participated in the project, and they read and approved the final manuscript.

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Data Availability The datasets are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors declare that they have no competing interests.

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Cong Wang received his Ph.D. degree from PLA University of Science and Technology, China in 2004. Now he is an associate professor at Army Engineering University of PLA. His research interests include mobile communications, M2M communications and computer networks



Chengqiang Wei was born in China, 1989. He is now working towards the M.S. degree in college of communications engineering, Army Engineering University of PLA. His research interests include M2M communications.



Ning Li received the M.S. degree from PLA Institute of Information Engineering in 1996. He is currently associate professor in PLA University of Science and Technology (PLAUST). His main research interests include Ad hoc network, cognitive wireless networks, soft-defined radio, and wireless communication.



Wenfeng Ma was born in 1974. He received the B.S. degree in microwave communication from the Institute of Communications Engineering, Nanjing, China, in 1995, and the M.S. degree in communications and information system from the Institute of Communications Engineering, Nanjing, China, in 1998, and the Ph.D. degree in communications and information system from the PLAUST (PLA University of Science and Technology), Nanjing, China, in 2002. From Apr. 2004 to Feb. 2006, he was a Postdoctoral Fellow with Shanghai Jiao Tong University (SJTU), Shanghai, China. He is currently a associate professor with the Army Engineering University of PLA. His research interests include wireless communication networks, broadband wireless communications.



Hui Tian received the B.S. degree in Communication Engineering from Tianjin University in 2009, received his M.S. degree and Ph.D. degree in Communication and Information Systems from PLA University of Science and Technology, Nanjing, China, in 2012 and 2016, respectively. He is currently a lecturer in the College of Field Engineering, Army Engineering University, Nanjing, China. His research interests are focus on wireless heterogeneous communication, cognitive radio networks, Internet of Things, wireless self-organized wireless network etc.