# Performance Analysis of Access Class Barring for Handling Massive M2M Traffic in LTE-A Networks

Israel Leyva-Mayorga, Luis Tello-Oquendo, Vicent Pla, Jorge Martinez-Bauset, and Vicente Casares-Giner
*ITACA Research Institute*
*Universitat Politècnica de València, Spain*
*Email:* {*isleyma,luiteloq,vpla,jmartinez,vcasares*}*@upv.es*

***Abstract*—The number of devices that communicate through the cellular system is expected to rise significantly over the coming years. But cellular systems, such as LTE-A, were designed to handle human-to-human traffic. Hence, they are not suitable for managing massive machine-to-machine communications. Therefore, additional congestion control methods must be developed and evaluated. Up to date, access class barring (ACB) and extended access barring (EAB) methods are the preferred solutions for reducing congestion in the access channels of the evolved NodeB. These methods are based on restricting the access of certain classes of UEs, so the system capacity is not exceeded. Due to the high complexity of the LTE-A system, evaluating its performance is not straightforward. Specifically, a large number of variables, coexistent mechanisms, and test scenarios make it difficult to identify the network parameters that enhance performance. In this paper, we analyze the ACB method in highly congested environments. For this, we evaluate the effect of ACB parameters (barring rates and barring times) by means of several key performance indicators (KPI) such as delay, energy consumption (preamble transmission attempts required) and success probability. We observed that ACB is appropriate for handling sporadic congestion intervals in LTE-A networks.**

***Index Terms*—Access class barring (ACB); cellular-systems; machine-to-machine communications; performance analysis.**

## 1. Introduction

In the near future, a massive number of interconnected devices will provide ubiquitous access to information and services. These devices, known as user equipments (UEs), are set to exchange information autonomously through machine-to-machine (M2M) applications, where a bulk of UEs transmit sparingly over time. Since cellular networks present a widely deployed infrastructure, these are the best solution for UE interconnection. Nevertheless, cellular technology was developed to handle human-to-human (H2H) traffic, where few devices (compared to the number of expected M2M devices) communicate simultaneously. Hence, congestion occurs when a massive number of devices attempt to access cellular base stations (known as evolved NodeBs (eNBs) in LTE-A).

Recent studies have demonstrated that the actual random access (RA) procedure is not efficient for managing massive M2M communication, as the physical random access channel (PRACH) suffers from overload when a large number of UEs compete for resources [1], [2]. As a result, several congestion control methods based on resource allocation [3] and reservation [4] have been proposed to enhance network performance and controlling PRACH overload.

The 3GPP suggests the use of access class barring (ACB) method along with extended access barring (EAB) method for congestion control in LTE-A [5]. On the one hand, in ACB each UE may randomly delay its RA according to a barring rate, $P_{ACB}$, and a barring time, $T_{ACB}$; these parameters are broadcasted by the eNB. ACB may be implemented statically (always active) or dynamically (only active when congestion occurs). On the other hand, the access of certain UEs may be dynamically barred in EAB, depending on the congestion of the access channel. As such, both methods use different mechanisms to spread UE access over time. Consequently, ACB and EAB may be effective whenever the congestion occurs sparingly and during short periods of time (in the order of a few seconds). This fact goes in line with the bursty traffic behavior described in [6], where congestion occurs sporadically. However, the performance analysis of ACB in these scenarios has been largely overlooked.

In this paper, we perform a thorough performance analysis of ACB in a transient massive M2M access scenario. For this, we consider a bursty traffic model and obtain the key performance indicators (KPI) defined by the 3GPP [7] for a wide range of barring rates, $P_{ACB}$, and barring times, $T_{ACB}$. By doing this, we are able to identify the combinations of these ACB parameters that enhance the access success probability, $P_s$, and also improve the trade-off between the access delay, and the number of transmissions required to access the network (which is closely related to energy consumption).

During this study, we closely follow the 3GPP recommendations, as we have observed that other studies tend to misinterpret ACB behavior, i.e., we have observed that most studies analyzing the performance of ACB assume a fixed barring time, but the 3GPP specifies that this parameter is selected randomly [8], [9]. Hence, to the best of our knowledge, we are the first to evaluate ACB with a random barring time, $T_{ACB}$. In addition, we consider the coexistence of H2H and M2M devices during RACH access, and also compare the KPIs obtained by implementing a uniform backoff (as stated in the LTE-A standard [5]) with an exponential backoff policy for M2M devices.

The rest of the paper is organized as follows. We conduct a review of studies analyzing the random access procedure in Section 2. Then, we describe the random access procedure, access class barring and the selected traffic model for this study in Section 3, Section 4 and Section 5 respectively. Our most relevant results are presented in Section 5.3 and finally, we present our conclusions.

## 2. Related Work

Several studies have demonstrated that the current random access procedure in LTE-A is not capable of handling massive M2M communications, but those studies usually overlook the effect that the ACB application has on the network performance. In fact, the complexity of the RA procedure and traffic models make it difficult to evaluate ACB properly. For instance, a thorough mathematical analysis of the RA procedure is performed in [6]. In fact, authors evaluate the performance of LTE-A when the congestion presents a transient behavior (as expected in most M2M applications) and obtain several KPIs specified by the 3GPP but neither ACB nor EAB are evaluated.

In [10], authors obtain the LTE-A system capacity, $c$ UE access per RA opportunity, and propose a dynamic congestion control solution. The performance of this solution is evaluated in terms of access success probability and compared with static ACB. Here, since the ACB analysis is performed for a very limited selection of barring rates and barring times, the advantages of the proposed solution are magnified. Furthermore, the barring time is assumed to be constant, whereas the 3GPP states in [9] that the barring time should be calculated randomly. This fact may negatively affect the performance of ACB.

The latter is a common problem in ACB analysis which is also present in [11], where a dynamic approach for selecting the optimal barring rate is presented. Here, authors select a constant barring time of one time slot, which highly differs from the protocol specification [8], [9]. Also, they assume the eNB is capable of updating and broadcasting the optimal barring rate at the beginning of each time slot, which may not be possible.

In fact, while dynamic ACB methods may present a better solution than static ACB for congestion control in LTE-A, their implementation is not straightforward. This is because the thresholds of network congestion statistics must be adequately selected to avoid the degradation of performance at specific times. Specifically, the activation and deactivation of dynamic barring methods is based on network congestion statistics (such as the ratio of transmitted preambles to granted access), which are dramatically altered whenever the barring methods are active [11], [12]. This fact is also observed for EAB in [13], where it is demonstrated that its efficiency highly relies in the selected paging cycle (period of time between updates of network congestion statistics and the transmission notifications to the UEs) as collisions are likely to occur before the EAB mechanism take effect and after removing the access restriction.

## 3. Random Access Model

This section provides a general overview of the RA procedure of LTE-A networks. RA can operate in two modes: contention-free and contention-based. The former is used for critical situations such as handover, downlink data arrival or positioning. The latter is the standard mode for network access, it is used by UEs to change the Radio Resource Control state from idle to connected, to recover from radio link failure, to perform uplink synchronization or to send scheduling requests [5].

Random access attempts are allowed in predefined time/frequency resources herein called RA opportunities (RAOs). The eNB broadcasts the periodicity of the RAOs by means of a variable referred to as the PRACH Configuration Index. The periodicity varies between a minimum of 1 RAO every 2 frames, i.e., 1 RAO every 20 ms, and a maximum of 1 RAO per 1 sub-frame, i.e., every 1 ms [2], [14].

The PRACH is used to signal a connection request when a UE desires to access the cellular network. The PRACH carries a preamble (signature) for initial access to the network. There are up to 64 orthogonal preambles available to the UEs per cell [14]. In contention-free mode there is a coordinated assignment of preambles, so collision is avoided, but eNBs can only assign these preambles during specific slots to specific UEs. Hence, UEs can only use these preambles, if assigned by the eNB, and during the specific slots. In the contention-based mode, preambles are selected in a random fashion by the UEs, so there is risk of collision, i.e., there is a probability that multiple UEs in the cell pick the same preamble signature; therefore contention resolution is needed. In the sequel, we focus on contention-based random access mechanism.

### 3.1. Contention-based Random Access Procedure

In Fig. 1, the message exchange in the RA procedure is illustrated. The eNB broadcasts information (through System Information Blocks) with the RA slots in which the preamble transmission is allowed (RAOs); in each of these RAOs, the eNB reserves a number of preambles for UEs to perform RA. Whenever a UE attempts transmission, it sends a randomly chosen preamble in a RAO (*Msg1*) and waits for $T_{RAR}$ sub-frames (needed for the eNB to process the preamble). Then, the eNB sends the RA response (*Msg2*); it includes, among other data, information about identification of the detected preamble and uplink grant for *Msg3* transmission. Note that if more than two UEs have chosen the same preamble in the same RAO, a collision will occur. The eNB can detect a non-collided preamble transmission with certain probability, $P_d$, which depends on several parameters, such as the transmission power of the UE. UEs that do not receive the *Msg2* within the random

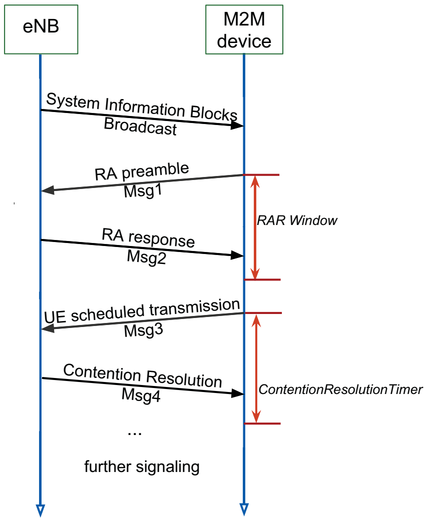



Figure 1. LTE-A Contention-based RA Procedure

access response (RAR) window, $W_{RAR}$, should ramp up its power and re-transmit a new randomly chosen preamble in a new RAO based on a uniform backoff policy. Non-collided UEs will exchange *Msg3* with eNB through dedicated channels and hybrid automatic repeat request (HARQ) is used to protect the message transmission. The eNB transmits a Contention Resolution message (*Msg4*) as an answer to *Msg3*. A UE which does not receive *Msg4* declares a failure in the contention resolution and schedules a new access attempt, i.e., a new preamble transmission, starting the process all over again. Each UE keeps a preamble transmission counter that is increased after each failed attempt. When the counter reaches the $preambleTransMax$ (informed as system information by the eNB), the network is declared unavailable by the UE and a RA problem is indicated to upper layers, i.e., random access is terminated [2], [5], [8], [12], [15].

**3.1.1. Backoff procedure.** According to the LTE-A standard [5], if the RA attempt of a UE fails, regardless of the cause, the UE has to start the RA process over again. For this, the UE waits for a random time, $U(0, BI)$ ms, until it can try again; $BI$ is the backoff indicator defined by the eNB and its value ranges from 0 to 960 ms. Herein, we also studied the potential benefits of implementing an exponential backoff policy, where the backoff time depends on the number of preamble transmissions, $P_t$, attempted previously by $T_{BO} = U(0, 10 \times 2^{P_t - 1})$. Note that $P_t \leq preambleTransMax$.

## 4. Access Class Barring

Access class barring (ACB) is a congestion control method that redistributes the access requests of UEs through time to reduce the number of access requests per RAO. ACB is applied to the UEs before they perform the RA procedure explained in Section 3.1. For this, UEs are divided into access classes (ACs) 0 to 15 according to its traffic characteristics; each UE can belong to one out of 10 ACs (from ACs 0 to 9) and to one or more out of the 5 special categories (ACs 11 to 15).

As mentioned before, if ACB is not operating, all classes are allowed to access the PRACH. When ACB is operating, the eNB broadcasts (through System Information Block Type 2) mean barring times, $T_{ACB} = \{4, 8, 16, \ldots, 512\,\mathrm{s}\}$, and barring rates, $P_{ACB} = \{0.05, 0.1, \ldots, 0.95\}$, that are commonly applied to ACs 0-9. Then, at the beginning of the random access procedure, each UE generates a random number between 0 and 1, $U[0, 1)$. If this number is less than or equal to $P_{ACB}$, the UE sends its preamble. Otherwise, the UE waits for a random time $T_{barring} = (0.7 + 0.6 \times rand) \times T_{ACB}$; where $rand = U[0, 1)$ [8], [9]. This process is repeated until the UE generates a random number lower than $P_{ACB}$ and sends its preamble. It is worth noting that ACB is particularly useful when RA requests occur in a bursty manner, i.e., a large number of UEs attempt transmission at a given time but the system is usually not congested. In other words, ACB spreads the load offered to the system through time, but in the long run, the total offered load is kept the same.

## 5. RACH Evaluation

Comparing novel congestion control methods is not straightforward due to the large number of variables and test scenarios. For that reason, 3GPP TR 37.868 [7] defines two different traffic models (see Table 1) and five KPI for the evaluation of the network performance with M2M communications. This allows a fair comparison of novel congestion solution proposals.

Table 1. M2M Traffic Models for RACH Evaluation [7]

| Characteristics | Traffic Model 1 | Traffic Model 2 |
|---|---|---|
| Number of M2M devices ($N_2$) | 1000, 3000, 5000, 10000, 30000 | 1000, 3000, 5000, 10000, 30000 |
| Arrival distribution | Uniform distribution over T | Beta(3,4) distribution over T |
| Distribution period (T) | 60 seconds | 10 seconds |

### 5.1. Traffic Models for M2M communications

Traffic model 1 can be considered as a typical scenario in which M2M devices access the network uniformly over a period of time, i.e., in a non-synchronized manner. Traffic model 2 can be considered as an extreme scenario in which a large amount of M2M devices access the network in a highly synchronized manner, e.g. after an application alarm that activates them.

### 5.2. Evaluation of the RACH and Performance Metrics

In order to evaluate the network performance, a single cell environment is assumed. The system accommodates H2H and M2M UEs. The network is subjected to different access intensities; for H2H we consider $N_1$ UEs whose access attempts are distributed uniformly over time, with an arrival rate of $\lambda_1 = 1$ per second; M2M devices follow the traffic model 2 detailed in Table 1.

There is 1 RAO every $5\,ms$ and $M = 54$ out of the 64 available preambles are used for contention-based RA. Under these conditions, the system offers 200 RAOs per second; $preambleTransMax$ is set to 10.

If two (or more) UEs select the same preamble at the same RAO, it is assumed that the eNB will not be able to decode any of the preambles; hence, the eNB will not send the Random Access Response (*Msg2*). UEs will only detect a collision if Msg2 is not received in the RAR window.

The five KPI for the purpose of RACH capacity evaluation are the following [7]:

1) Collision probability, defined as the ratio between the number of occurrences when two or more MTC devices send a random access attempt using exactly the same preamble and the overall number of opportunities (with or without access attempts) in the period.
2) Access success probability, $P_s$, defined as the probability to successfully complete the random access procedure within the maximum number of preamble transmissions.
3) Statistics of the number of preamble transmissions per access attempt, $P_t$.
4) Statistics of access delay.
5) Statistics of simultaneous preamble transmissions.

We developed a discrete-event simulator in C that allows us to obtain these KPIs. Additionally, these results were corroborated with Matlab simulations independently. In each simulation, $N_2$ UE arrivals are distributed in $T$ seconds and the contention-based RA procedure described in Section 3.1 is replicated with the parameters listed in Table 2. Simulations are run $j$ times until the results from the $j$ th differ from the $j-1$ th simulation by less than $1\%$. Table 2 lists the parameters used in this paper.

Table 2. Basic Simulation Parameters for RACH Evaluation

| Parameter | Setting |
|---|---|
| Cell bandwidth | 5 MHz |
| PRACH Configuration Index | 6 |
| M2M Attempts distribution | Beta(3,4) |
| Total number of preambles (M) | 54 |
| $preambleTransMax$ | 10 |
| Number of uplink grants per RAR | 3 |
| Preamble detection probability for the $P_t\,th$ preamble transmission | $P_d = 1 - \frac{1}{e^{P_t}}$ |
| $W_{RAR}$ | 5 sub-frames |
| $mac\text{-}ContentionResolutionTimer$ | 48 sub-frames |
| Backoff Indicator (BI) | 20 ms |
| HARQ re-transmission probability for Msg3 and Msg4 (non-adaptive HARQ) | 10% |
| Maximum number of HARQ TX for Msg3 and Msg4 (non-adaptive HARQ) | 5 |
| Periodicity of RAOs | 5 ms |
| Preamble transmission time | 1 ms |

## 5.3. Performance Analysis of ACB

In this section we present some relevant results derived from our performance analysis of ACB for handling massive M2M traffic.

As a baseline, Fig. 2 illustrates the average number of UE arrivals (first preamble transmissions), successful preambles, successful access (UEs that receive a RAR),

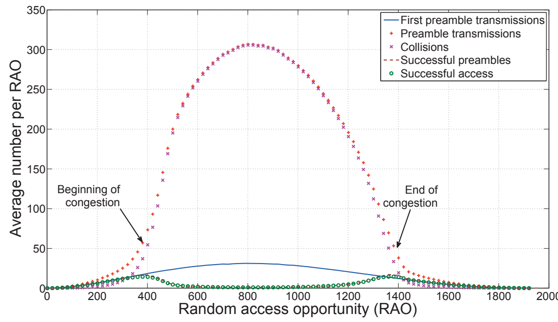



Figure 2. LTE-A, Temporal distribution of M2M UE access, Traffic model 2, $N_2 = 30000$, uniform backoff.

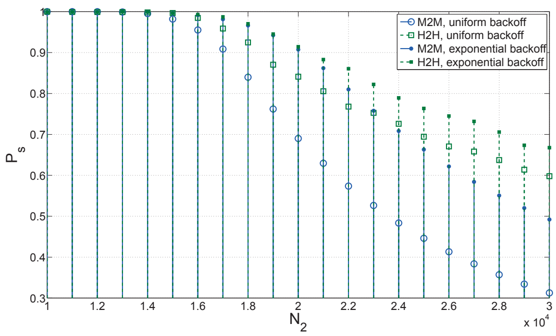


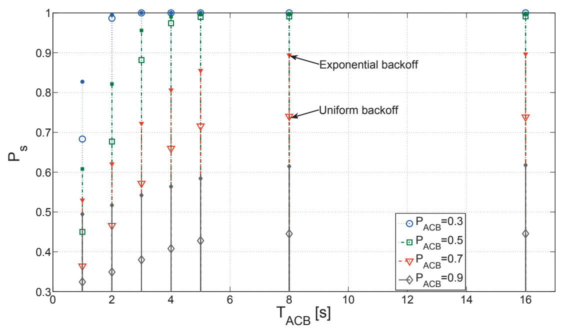

Figure 3. LTE-A, Access success probability, H2H with arrival rate of $\lambda_1 = 1s^{-1}$, M2M follows Traffic Model 2, $10000 \leq N_2 \leq 30000$, Uniform and Exponential backoff policies in the RA procedure.

preamble transmissions and collisions per RAO for the scenario described in 2 without applying ACB.

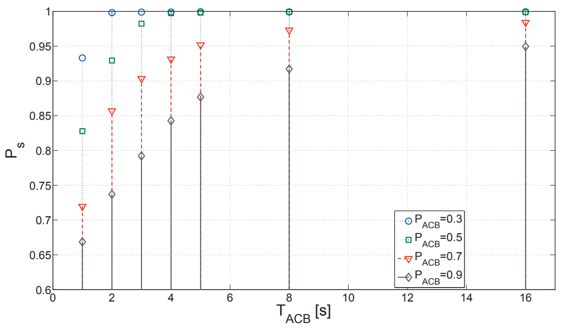
Note that Traffic model 2 leads to network congestion when $N_2 = 30000$; the Beta(3,4) distribution of UE accesses causes the PRACH capacity ($c = 20.05$ UE access per RAO, as calculated in [10]) to be exceeded for a time period $T_c \approx 4\,s$. As a result, $P_s$ sharply decreases. As mentioned in Section 3.1.1, once a collision occurs, the UEs must wait a backoff time until they can try the RA again. For this, we have studied two cases. In the first one, UEs perform a uniform backoff, $U(0, BI = 20)\,ms$ as defined in the standard [5]. In the second one, the backoff time depends on the number of preamble transmission attempts of each UE, $P_t$, as $T_{BO} = U(0, 10 \times 2^{P_t - 1})$; $P_t \leq preambleTransMax$. Figure 3 compares the $P_s$ of M2M and H2H UEs when implementing the uniform and the exponential backoff. It is observed that $P_s$ decreases when selecting traffic model 2 and $N_2 > 15000$ as the system capacity is temporally exceeded. This is not observed when selecting either Traffic model 1 or Traffic model 2 with $N_2 \leq 15000$.

From Fig. 3 we also observe that a higher $P_s$ is achieved by implementing an exponential backoff, but is not sufficient to solve the congestion in the PRACH.

For the remainder of this paper, our performance analysis of ACB is conducted by distributing $N_2 = 30000$ UE arrivals over $T = 10\,s$, as it is the most congested




(a) M2M




(b) H2H

Figure 4. Access success probability of M2M and H2H UEs when ACB is operating, Traffic model 2, $N_2 = 30000$.

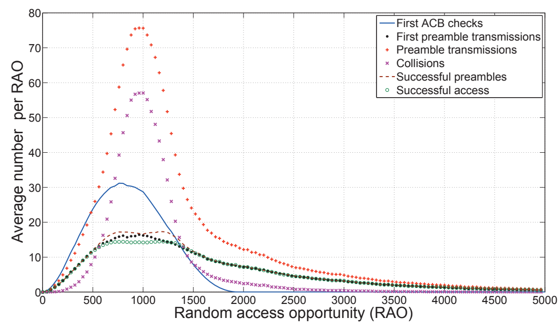



Figure 5. Temporal distribution of M2M UE access when ACB is operating, Traffic model 2, $P_{ACB} = 0.5$ and $T_{ACB} = 4\,s$, $N_2 = 30000$, uniform backoff.

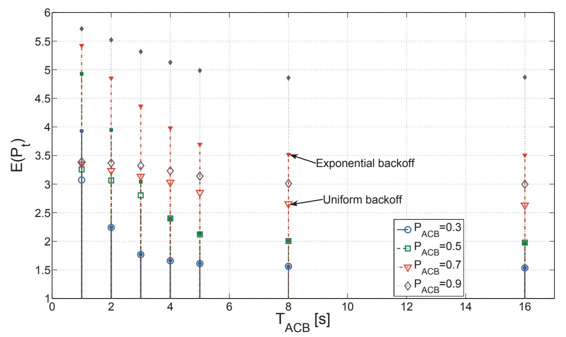



Figure 6. Mean number of preamble transmissions for the successfully accessed M2M UEs when ACB is operating, Traffic model 2, $N_2 = 30000$.

scenario defined in Traffic model 2 by the 3GPP. We assess the performance of ACB in terms of three KPIs, i.e., the access success probability, $P_s$, the mean number of preamble transmissions, $E(P_t)$ (which is closely related to energy consumption), and access delay.

First, we are interested in obtaining the ACB parameters that result in an acceptable $P_s$. Specifically, we analyze several barring rates, $P_{ACB}$, and barring times, $T_{ACB}$, to identify the combinations that result in $P_s \geq 0.95$. We observe from Fig. 4a that lower barring rates, $P_{ACB}$, in combination with larger barring times, $T_{ACB}$, enhance $P_s$. Specifically, $P_s \geq 0.95$ for M2M UEs is only achieved when selecting $P_{ACB} \leq 0.5$, which prevents that the number of UE access per RAO exceeds the system capacity.

When comparing the $P_s$ achieved by the uniform backoff and the exponential backoff, we observe that, for the latter, lower barring times are needed to achieve $P_s \geq 0.95$ for both, M2M UEs, see Fig. 4a, and H2H UEs, see Fig. 4b.

To illustrate the effect of ACB, we obtained the average number of first ACB checks, preamble transmissions, collisions and successful access per RAO when selecting $P_{ACB} = 0.5$ and $T_{ACB} = 4\,s$. These results are shown in Fig. 5, where we observe a dramatic reduction in the number of collisions and preamble transmissions RAO when compared with those of Fig. 2.

To further study the behavior of UE access while ACB is active, we obtained the mean number of preamble transmissions for the successfully accessed UEs, $E(P_t)$. In Fig. 6 we observe that when selecting a uniform backoff policy, the UEs usually succeed during the first few preamble transmissions. We also observe that $E(P_t)$ increases along with $P_{ACB}$. Low values of $T_{ACB}$ also increase $E(P_t)$. Note that in cases where the exponential backoff increases $P_s$ (when compared to the uniform backoff), $E(P_t)$ also increases. As such, implementing an exponential backoff policy may slightly increase $P_s$ at the cost of increasing energy consumption. In cases where both backoff policies would lead to $P_s \geq 0.95$, $E(P_t)$ is almost identical.

Finally, we studied the access delay when ACB is operating. For this, we calculate delay as the time elapsed between the first ACB check of a UE and the successful completion of its RA procedure, according to the values from table 16.2.1-1 in [16]. For the sake of simplicity, we obtained percentiles of delay, defined as the delay experienced by a fraction, $\delta N$, of the UEs, where $\delta \in \{0.1, 0.5, 0.95\}$. As such, Fig. 7 illustrates the 10 th percentile, $P_{10}$, the 50 th percentile, $P_{50}$, and the 95 th percentile, $P_{95}$, using the uniform backoff policy. The experienced delay with the exponential backoff policy in the RA procedure is qualitatively similar for the cases of interest.

As expected, a combination of low values of $T_{ACB}$ with high $P_{ACB}$ leads to a reduction in the access delay. In fact, the lowest access delay, given $P_s \geq 0.95$, is achieved when selecting $T_{ACB} = 4$ and $P_{ACB} = 0.5$. Also, while

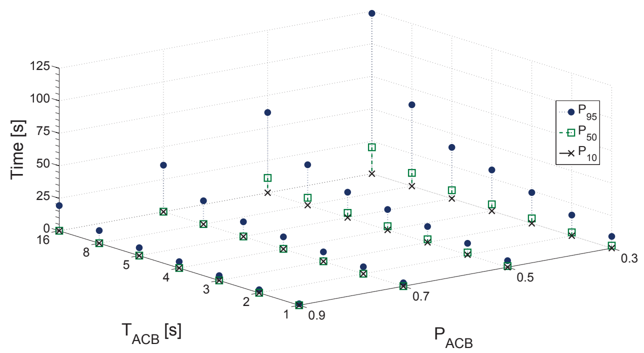



Figure 7. Access delay of M2M UEs when ACB is operating, Traffic model 2, $N_2 = 30000$, uniform backoff.

large $T_{ACB}$ do not greatly affect $P_s$, see Fig. 4, we observe in Fig. 7 that access delay sharply increases along $T_{ACB}$. Hence, a large $T_{ACB}$ should be avoided.

## 6. Conclusion

We have studied the access class barring (ACB) method for dealing with excessive PRACH overload and analyzed the impact that barring rates, along with barring times, have on the network performance. The selected traffic model describes the bursty arrivals of a massive number of M2M UEs to an eNodeB. We assume that access success probability, $P_s$, is the main key performance indicator (KPI), hence we first focus on identifying the combinations of barrings rates and barring times for which $P_s \geq 0.95$ is achieved. Then we studied other KPIs such as the number of preamble transmissions and the access delay, where we identified a trade-off. Specifically, low barring rates and large barring times increase the access delay but reduce the number of preamble transmissions, hence reducing energy consumption. It is worth noting that the relevance of energy consumption and access delay highly depends on the traffic characteristics, i.e., the frequency of random access congestion. For instance, if the studied scenario occurs sparingly, these KPIs are not highly relevant, as slight increases in energy consumption will not highly affect the battery life. On the other hand, when this scenario occurs frequently, battery life may be compromised and highly delayed access may cause congestion in subsequent UE access.

We also compared the KPIs obtained by implementing a uniform backoff policy (as described in the LTE-A standard) with an exponential backoff policy for the random access procedure. Results show that an exponential backoff leads to a higher success probability but also increases the mean number of preamble transmissions. Therefore, implementing an exponential backoff may enhance access success probability at the cost of a higher energy consumption.

Finally, by adequately selecting ACB barring rates and barring times, network congestion may be relieved, even for the most congested scenario defined by the 3GPP. As such, ACB is an effective method for congestion control in the PRACH.


## Acknowledgment

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