Massive Access in the Random Access Channel of LTE for M2M Communications: an Energy Perspective

Andres Laya*, Luis Alonso†, Periklis Chatzimisios‡ and Jesus Alonso-Zarate§

*KTH Royal Institute of Technology, Sweden. e-mail: laya@kth.se

†Universitat Politècnica de Catalunya (UPC), Spain. e-mail: luisg@tsc.upc.edu

‡Alexander TEI of Thessaloniki, Greece. e-mail: peris@it.teithe.gr

§Centre Tecnològic de Telecomunicacions de Catalunya (CTTC), Spain. e-mail: jesus.alonso@cttc.es

***Abstract*—The capacity limits of the Random Access Channel (RACH) of Long Term Evolution (LTE) for highly dense Machine-to-Machine communications are studied in this paper. We consider the case study when a high number of devices attempt to transmit information to the same base station in a very short period of time. Simulations have been performed considering several parameter configurations related to the random access procedure of LTE. The energy consumption is used as a primordial metric to compare any improvement regarding the random access procedure in future releases, in order to evaluate the impact on the battery lifetime of autonomous devices.**

Keywords*—*Machine-to-Machine, Random Access Channel, LTE, Energy Efficiency.

I. Introduction

Today, two terms are commonly used to refer to the automated exchange of data among devices without involving, or minimizing, human intervention; these terms are Machine-to-Machine (M2M) and Machine Type Communication (MTC), in 3GPP terminology. Both refer to basic data collection and transmission over a communication network to facilitate smart applications [1]. Smart metering, smart cities, smart grids, mHealth, supply chain tracing, fleet management, remote control, industrial automation are some key examples of applications that can be accomplished if energy-efficient M2M networks can become a reality. Market studies expect that the number of autonomous interconnected devices will surpass the number of Human-to-Human (H2H) connections in developed countries in the near future. This poses severe challenges to existing network infrastructures that have been designed and deployed particularly for H2H communications. This is the case of cellular networks, which are envisioned to play a key role in the success of M2M applications due to their advantages with regard to short-range solutions [2]. Ubiquitous coverage, roaming, already installed infrastructure and known-technology, or the use of dedicated frequency bands to control interference (one of the main headaches of systems operating in license-free bands), are among the list of key advantages of cellular networks to become facilitators of M2M.

International standardization bodies, such as ETSI and the 3GPP, had raised concerns on the impact that this additional communication pattern will have over the available networks [3]. The fact that communication technologies were not conceived to fulfill the requirements of M2M (rather those of H2H), require optimization studies to understand and improve the management of data and signaling traffic related to M2M devices over cellular systems, without jeopardizing the service offered to humans [4], [5]. Among other challenges, 3GPP has released a technical report that stresses the need to design improvements for the access mechanisms of cellular systems to be able to handle applications where the number of subscribers raises up to tens of thousands per cell [6]. This can highly affect the access performance for H2H users as presented in [7]. This is the motivation of the work presented in this paper, where we focus on the Random Access Channel (RACH) of LTE.

The scope of our work is the quantitative evaluation of LTE RACH and the provided contributions focus on the analysis of LTE limits to support M2M communications; we analyze the overload and scalability issues. Although, many improvements can be found in the literature, the actual limits of the RACH have not been quantified yet. This study does not only evaluate performance in terms of access delay but also studies energy consumption with particular emphasis on the energy impact over battery-constrained devices, a factor that has been largely disregarded by many RACH related studies, as presented in [8]. The energy consumption is extremely significant in order to determine which improvements may be feasible without entailing negative outcomes on the efficiency of devices that depend on restricted energy sources. We study scenarios with extreme access load that might be caused by a power failure or the massive generation top-priority alarms. Our work is based on simulations performed on ns-3 simulation software [9].

The remainder of the paper is organized as follows: section II describes in detail the operation and in particular the contention-based random access procedure of LTE. Consequently, Section III provides related work on improvements for MTC. Section IV describes the simulation model that has been developed and utilized in order to evaluate the considered simulation scenarios. Furthermore, simulation performance results about LTE RACH are also provided. Finally, conclusions and future research topics are devised in Section V.

II. LTE Random Access Procedure

Mobile equipment suited for MTC are referred to as M2M Device, it requests access to the eNodeB in the following cases:

1) During the association phase (initial access).
2) For data resource requests.
3) When performing handover to a different eNodeB.
4) Connection re-establishment after a radio link failure.

There are two forms of Random Access (RA) in LTE:

- Contention-based, for access requests that can tolerate delay (prone to collisions).
- Contention-free, for access requests that require high probability of success, such as handover process.

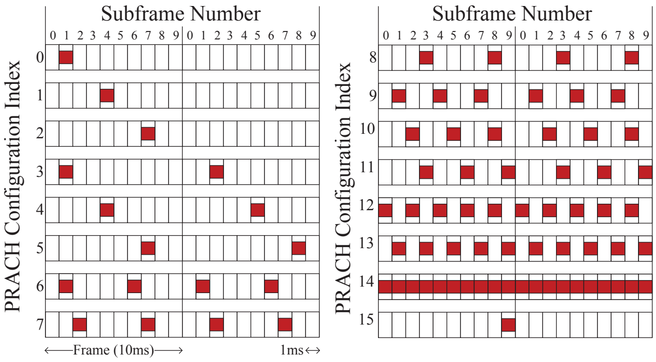

Fig. 1. PRACH Configuration Indexes.

This paper focuses on the contention-based RA for the initial access case, corresponding to the transition from idle to connected state at the Radio Resource Control (RRC) level.

A. *Definitions*

Before examining the actual access procedure, it is important to understand two key concepts:

RANDOM ACCESS PREAMBLE: it is a signature used by devices to request access to the network. RA Preambles are generated by cyclic shifting a root sequence. In total, there are 64 available preambles and the eNodeB is capable of allocating a number N_{cf} of those preambles for contention-free access, leaving $64 - N_{cf}$ preambles available for contention-based access. The number of preambles that are available for each form of RA are broadcast by the eNodeB in the broadcast downlink channel as part of the system information [10]. Devices following the contention-based procedure will randomly selects one of the available preambles when attempting to access the network and transmit it over the RACH. The duration of the preamble depends on the size of the cell, and can vary from 1 to 3 ms. The larger the cell-size, the longer the preamble to ensure its proper reception. If all the preambles are generated from the same root sequence they are orthogonal to each other. In such case, different preambles from multiple M2M Devices can be detected by the eNodeB when they are transmitted in the same cell at the same time.

RANDOM ACCESS SLOTS: are the periodic time-frequency resources in which the RACH is divided. This RA slots are reserved in the uplink channel for access request transmissions [11]. The duration depends on the preamble format and, in frequency domain, it requires 1.08Mhz, which are 6 Resource Blocks of the uplink channel. The variable that controls the number of access resources per frame is the *PRACH Configuration Index*, it is broadcast by the eNodeB in a RRC Message (specifically the System Information Block Type 2) [12]. Fig. 1 shows how the configuration index is mapped on the uplink channel subframes, the colored squares represent RA slots, i.e., the access opportunities in a frame.

Devices randomly select among these RA slots opportunities to transmit the preamble. There are, at most, 10 RA slots per LTE frame, i.e., every millisecond. And at least 1 RA resource every 2 LTE frames, i.e., every 20ms [10]. In total, there are 64 possible configurations [11], but they are based on the 16 shown in Fig. 1. The difference is that for some random access format the length of the preamble is longer than 1ms; therefore, the RA slots must be properly scattered in order to prevent overlaps. It is important to bear in mind that the physical resources for the PRACH decrease the resources available for the Physical Uplink Shared Channel (PUSCH) used for scheduled uplink transmissions. Therefore, it is necessary to properly compensate the PRACH and PUSCH allocation.

B. *Contention-Based Random Access Procedure*

When a User Equipment (UE) wants to connect to the LTE network, a four-message handshake is initiated, as shown in Fig. 2. This access attempt is considered successful when a device has completed the fourth-step of the procedure within the maximum attempts allowed.

Step 1 - MESSAGE 1, RA PREAMBLE TRANSMISSION: each device randomly selects a preamble from the available one) and transmits it over the next available RA slot. The eNodeB decodes the preamble and computes the associated Random Access Radio Network Temporary Identifier (RA-RNTI); this identifier is based on the physical resource where the preamble was sent [13]. A preamble collision occurs if more than one device sends the same preamble on the same RA slot. Devices that have transmitted a preamble wait for a time window to receive the Message 2. This window starts three subframes after the preamble transmission [13]. The length of the window is broadcast as Cell-Specific System Information and can last from 2 to 10 subframes [12].

Step 2 - MESSAGE 2, RANDOM ACCESS RESPONSE (RAR): if the eNodeB detects a preamble, it replies with the RAR. This message is sent over the Physical Downlink Shared CHannel (PDSCH) without HARQ and contains the following information:

- Identity of the detected preamble.
- Timing alignment instructions to synchronize uplink transmissions.
- Initial uplink resource grant, to be used in message 3.
- The assigned Temporary Cell Radio Network Temporary Identifier (C-RNTI).
- An optional Backoff Indicator (BI) to request the device to wait a period of time before retrying access in case of failure [13]. This is used to reduce the probability of preamble collision, dispersing the access attempts.

The RAR is addressed to the RA-RNTI, thus, to all the devices that transmitted a preamble on a specific access resource. The RAR contains different subheaders to deliver different information to each detected preamble. If a device receives a RAR addressed to its RA-RNTI but does not found the preamble it used, it will perform a backoff time according to the BI parameter [13].

If multiple devices select the same preamble and they send it over the same RA slot, the eNodeB might detect the collision based on the difference in transmission delay and it will not provide a RAR for this preamble. However, if the devices are at the same distance from the eNodeB, the collision might be undetected and the same RAR information will be decoded by more than one device.

Step 3 - MESSAGE 3, CONNECTION REQUEST: after the initial uplink resource grant informed in Message 2, the device transmits a connection request to the eNodeB. This information is transmitted with HARQ [12] and for the initial access it conveys the device identifier (C-RNTI) and the establishment

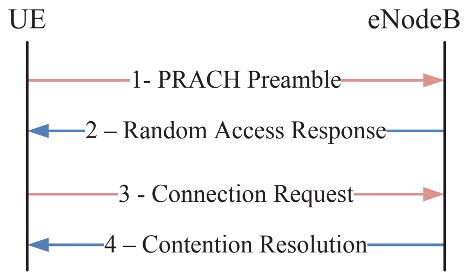

Fig. 2. Contention-Based Random Access Procedure.

cause. In case of undetected preamble collision, more than one device was assigned with the same uplink resource; the eNodeB will detect the collision and it will not acknowledge this message; causing HARQ retransmissions up to the maximum allowed before declaring access failure and scheduling a new access attempt.

Step 4 - MESSAGE 4, CONTENTION RESOLUTION: in the final step, the eNodeB transmits a contention-resolution message. Each device receiving this message compares the identity in the message with the identity transmitted in the previous step. A device detecting a match between these identities will have a successful access. If there is no match, a new access attempt is scheduled.

The number of access attempts per device is limited by a parameter that is transmitted as part of the system information, referred to as *preambleTransMax*. It corresponds to the maximum number of preamble transmission [13]. Each device keeps a preamble transmission counter. When an access attempt is unsuccessful, the device increments the counter and then compares it with *preambleTransMax*; if the counter have not reach the limit, the device schedule a new preamble transmission. Otherwise, the network is declared unavailable and a random access problem is indicated to upper layers.

In the following section we present efforts related to the improvement of the RA procedure for M2M communications.

III. RELATED WORK

The 3GPP TR [6] introduces the challenge related to the RACH capacity for M2M communications and proposes some approaches to overcome access congestion that have been later discussed in [14] and [15] and include the following proposals:

1) Slotted access: access slots are defined for M2M devices; each M2M device has its own dedicated access slot, associated with its ID in order to access the network.
2) Access Class Barring: traffic is split in different access classes such as normal device, metering device, emergency call, high-priority service, etc. The number of classes will depend on the granularity of the control needed among devices [6].
3) Dynamic Allocation of RACH Resources: the network can allocate additional RACH resources to M2M devices in case of congestion. But this solution is limited to the LTE maximum RACH resources.
4) Backoff Adjustment: differentiate backoff timers for traditional equipment and for M2M devices, assigning a higher value to the latter. This solution is considered to be sufficient in order to cope with peak congestion levels.

As explained by the 3GPP in [6], the previously reported methods are not sufficient to reach a satisfactory performance and random access improvements are still under research. Additional solutions have been proposed in the literature to overcome access congestions, some of these solutions has been compared in [16]. An alternative to automate the RACH optimization of LTE has been studied to properly configure the resource allocation for the random access during operation [17]. However, it does not study the effect that the M2M traffic might have on the performance if no additional improvements are integrated. Related to M2M traffic, the work in [18] proposes and compares two improved random access methods in terms of throughput. In one method, the available preambles are divided into two subsets: one is for H2H and the other for M2M traffic. In the other method, there are also two subsets; one for H2H and the other is shared by H2H and M2M devices. The derived performance indicate that the second method is more efficient at very high access loads. However, these solutions do not provide granularity to differentiate services and it is important to consider, for example, the fact that some M2M applications will have more restrictive access delay constrains than H2H applications, e.g., priority alarm reports. Another study [19] considers the increase of the available contention resources, without modifying the original system resources, i.e., contention sub-frames and preambles. The increase is accomplished in the code domain, with the so-called RA codewords. Devices send more than one preamble, each on a different access sub-frame. This solution improves the efficiency for high loads at the expense of multiple preamble transmission on each access attempt [19]. Several authors have proposed additional improvements but in most cases the energy impact of the proposals is not considered. This fact cannot be underestimated when it is expected that an important share of M2M devices will be powered by constrained energy sources. The work presented in [8] provides a novel evaluation framework for the analysis of the random access procedure, based on analysis and simulation. We extend the scope by analyzing different values of configuration parameters in the network simulation sets in order to understand the full extent that can be achieved with the current LTE RA scheme.

IV. PERFORMANCE EVALUATION

In this section, the performance of the standard RA procedure is evaluated under a feasibly M2M traffic load, according to [6]. The access delay and the total amount of energy required to gain network access are calculated. We next present the considered simulation models and system setup as well as the derived performance results.

A. Simulator

To conduct the performance evaluation, a LTE random access module has been developed in ns-3 simulator. Even though the official ns-3 release provides LTE modules, the random access procedures are not implemented. Moreover, the high amount of devices considered in our study resulted in extreme computational underperformance. For these reasons, we developed new modules to specifically simulate LTE's random access procedure in Frequency Division Duplex (FDD) mode. In order to validate the newly developed modules, simulations where done with the exact same parameters listed in the 3GPP TR 37.868 [6] using a time limited Beta distribution for traffic arrivals, specifically the $Beta(3, 4)$ function over 10 seconds.

TABLE I. VALIDATION OF NS-3 SIMULATION MODELS

		3GPP TR 37.868 Results			NS-3 Random Access Module		
Number of devices per cell		5000	10000	30000	5000	10000	30000
Performance Measure	Access Success Prob.	100,00%	100,00%	29,50%	100,00%	99,99%	34,23%
Number of preamble transmissions	Average	1,56	1,77	3,49	1,55	1,77	3,39
	10th percentile	1	1	1	1	1	1
	90th percentile	2,14	2,77	7,33	2,5	3	8
Access Delay (ms)	Average	29,06	34,65	76,81	29,67	33,95	66,43
	10th percentile	15	15,25	15,89	14,02	14,39	16,52
	90th percentile	51,61	65,71	174,39	50,80	61,56	152,64

The function's PDF is shown in Fig. 3. The comparison of the derived performance are illustrated in Table I, where the similitude between the results can be seen, even when simulating 30000 devices. The utilized configuration parameters will be explained in the next subsection.

B. System Setup

We assume a cellular LTE network where a number of M2M devices are cell-synchronized at the beginning of the simulation and they have already received all configuration parameters related to the RA procedure. Control signaling transmissions related to the system information are out of the scope of this work.

In order to understand the limits of the RACH of LTE, simulations where performed with more than one thousand devices that need to access the network on a very short period of time, following a $Beta(3,6)$ arrival distribution as shown in Fig. 3, over a period of 1 second. This scenario may be caused by the sudden appearance of a massive source of alarms or after a power outage. It is assumed that the eNodeB will not be able to decode simultaneous transmission of the same preamble; therefore, it will not send the RAR for those preambles.

The simulation parameters in Table II were utilized to understand the actual behavior of the network. The number of available preambles are the $64 - N_{cf}$ signatures available for the contention-based RA procedure; *preambleTransMax* correspond to the maximum number of access attempts a device can perform before declaring network unavailability; the Contention Resolution Timer is the maximum time a device waits to receive message 4 (contention resolution) after sending the connection request. The energy consumption parameters for the LTE interface are based on [20], with a device transmission power of 1,8W. We only focus on the energy efficiency of the devices. In particular, we study four key performance metrics:

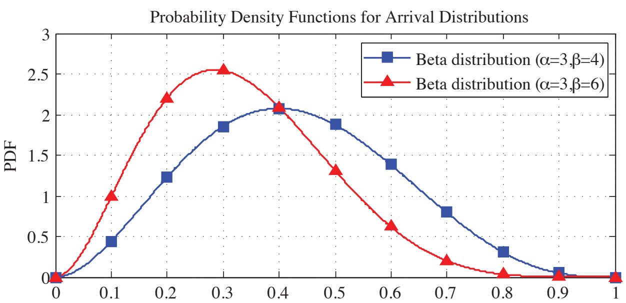

Fig. 3. Probability density functions, $Beta(3,4)$ over 10 seconds was used to validate the simulation models. $Beta(3,6)$ over 1 second was used in our scenario to simulate the traffic overload.

1) *Average Access Delay*: time elapsed form the first preamble transmission to the reception of message 4, only successful access are considered for the average calculation.
2) *Blocking Probability*: the probability of a device reaching the maximum number of attempts and being unable to complete an access process.
3) *Energy Consumption*: the total energy spent until the access to the network has been granted, only successful access are considered for the average calculation.
4) *Average Number of Preamble Retransmissions*: the number of attempts that the devices execute.

If a device reaches the maximum number of preamble transmission without gaining access is blocked by network. Therefore, the time elapsed during the access attempts and the energy consumed are not considered for the average calculation.

C. Performance Results

Three different experiments have been carried out. In the first one, the maximum number of preamble transmissions is fixed at 10 and the PRACH Configuration Index take the values 0, 3, 6, 9 and 12. In Fig. 4 it can be seen the average access delay (continued lines) and the blocking probability (discontinued lines) for different PRACH configurations; it can be appreciated how the blocking probability and the average access delay lower when the access opportunities per frame increases, basically because the attempts are dispersed and more resources are available.

The energy consumption of this experiment is also shown in Fig. 4; the relationship with the average number of preamble transmissions is very straightforward, more RA resources per frame result in less energy consumption per device and the average number of preamble transmission diminish due to the decrease in the preamble's collision probability.

For the second experiment, the PRACH Configuration Index is fixed to 6, i.e., 2 RA slots per frame; and different values for *preambleTransMax* are evaluated (3, 10, 15 and 50). In Fig. 5 it can be seen that when the number of maximum allowed retransmissions is higher, the average access delay increases drastically. For 50 allowed retransmissions, the access

TABLE II. SIMULATION PARAMETERS

Parameter	Simulated Values
PRACH Configuration Index [a]	0, 3, 6, 9, 12
Number of Available Preambles [b]	60
preambleTransMax	3, 10, 15, 50
RAR Window Size [c]	5 Subframes
Contention Resolution Timer [c]	48 Subframes
Backoff Indicator [b]	20ms

[a] See Fig. 1 for explanation of these values.
[b] All possible values available in 3GPP TS 36.321 [13].
[c] All possible values available in 3GPP TS 36.331 [12].

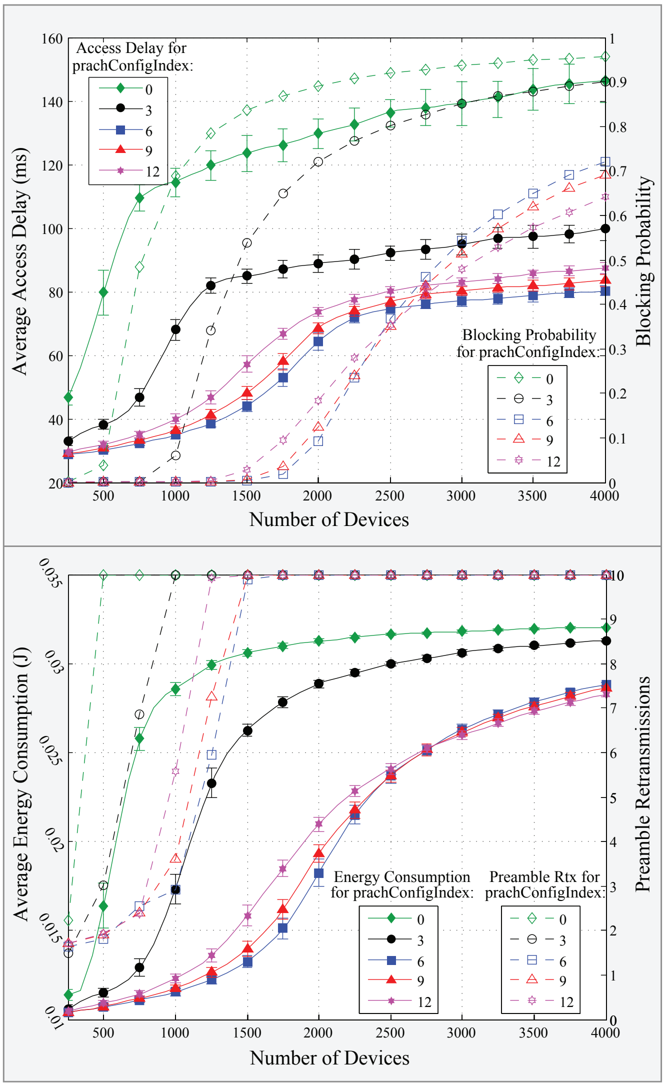

Fig. 4. Access delay and energy consumption for different PRACH Configuration Indexes. With maximum number of preamble transmissions per device (*preambleTransMax*) equal to 10.

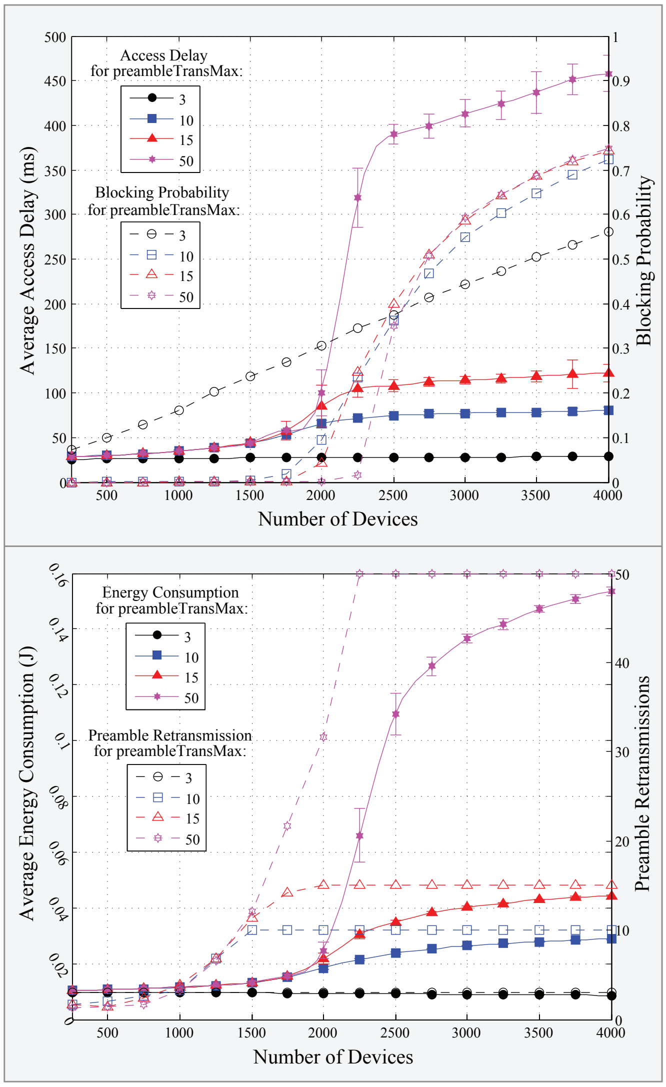

Fig. 5. Access delay and energy consumption for different maximum number of preamble transmissions per device. With PRACH Configuration Indexes (*prachConfigIndex*) equal to 6.

delay is almost 4 times higher than for the other configurations when that amount of devices is bigger than 2000 devices. Moreover, for 4000 devices the blocking probability is actually higher for 50 than for 3 or 10 allowed retransmissions; the reason is that for a lower number of opportunities some devices are blocked earlier and don't continue the contention. On the contrary, for 50 opportunities, devices continue retrying during the whole simulation period. To synthesize, more transmission does not necessarily improve the overall performance. As expected, the energy consumption increases for higher average number of transmission, as shown in Fig. 5.

The last experiment, which is shown in Fig. 6, corresponds to an additional congestion study. For this case, we only look at simultaneous arrivals, in order words, instead of using a Beta arrival distribution, the arrival distribution could be interpreted as a delta function. The objective is to show the behavior of the RACH of LTE when the number of preambles sent on a specific resource increases and then the following reattempts are scattered due to the BI. The X-axis in Fig. 6 will therefore correspond to the number of users trying to access simultaneously. 10 *preambleTransMax* where used with different PRACH Configuration indexes. It can be appreciated how the access delay is significantly lower when more access resources are allocated but the blocking probability and the average energy consumption demonstrate that the overall performance degrades when the number of simultaneous arrivals increases.

V. Conclusion

In this paper, we have quantified the limits of the RACH of LTE in terms of access delay and energy consumption in order to determine if the RA scheme used by the standard is suitable for M2M traffic. The experiments used beta and delta arrival distributions to illustrate bulk arrival conditions. The results obtained through computer simulations show that the access mechanism is not capable to manage the access requests from thousands of devices in time-constrained scenarios and therefore improvements are required. They also emphasize the

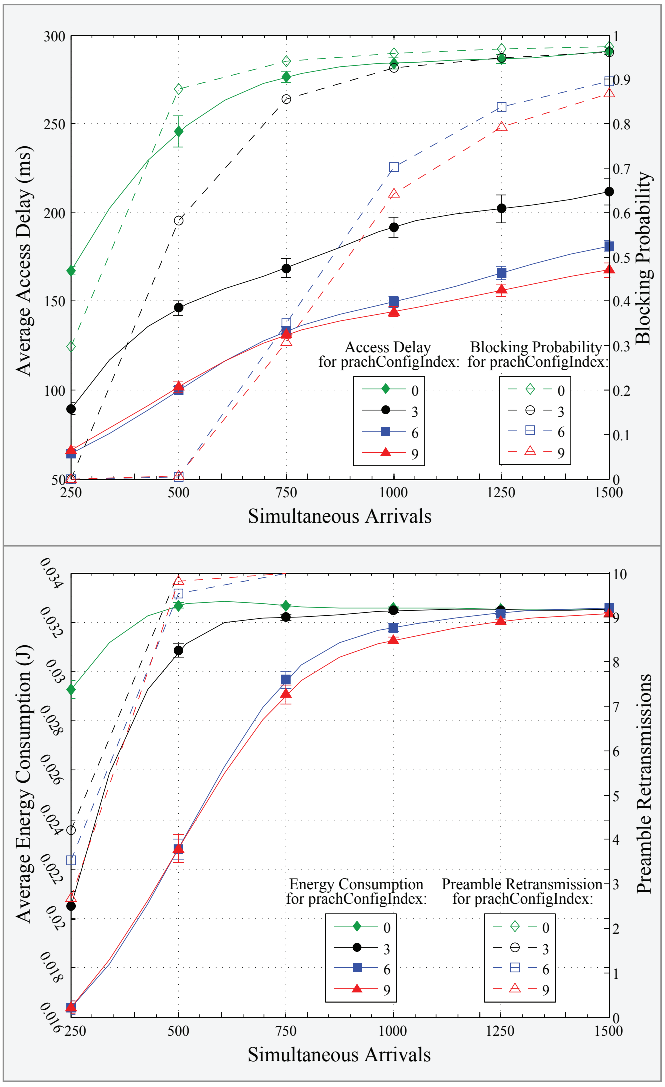

Fig. 6. Access delay and energy consumption for different number of simultaneous access request (simultaneous arrivals). Using different PRACH Configuration Indexes and maximum number of preamble transmissions per device (preambleTransMax) equal to 10.

fact that adaptations based on more preamble retransmissions or extended delays will have a direct negative impact in the energy consumption of the devices, a critical factor for battery-driven M2M devices.

Key parameters, such as the PRACH Configuration Index and the Maximum number of preambles transmission, have been modeled and evaluated using the NS-3 simulation environment in order to understand their behavior under various configurations and to provide a better insight of future improvements. It has been observed that some configurations may provoke a high increase in the energy consumption without improving the overall performance of the network.

Future work will be focused on proposing mechanisms to both improve the access delay performance and the energy efficiency of the RACH while ensuring low blocking probability rates. The aim will be to successfully satisfy the requirements of M2M communication scenarios where the presence of high density of devices per base station with correlated, yet uncoordinated, transmission times must be efficiently handled.

Acknowledgment

This work has been partially funded by Wireless@KTH, The EIT ICT Labs project EXAM, ADVANTAGE (FP7-607774), P2P-SMARTEST (H2020-646469), the Catalan Government under grant (2014-SGR-1551) and the fellowship program SENER-UPC.

References

[1] A. Laya, L. Alonso, P. Chatzimisios, and J. Alonso-Zarate, “Reliable machine-to-machine multicast services with multi-radio cooperative retransmissions,” *Mobile Networks and Applications*, pp. 1–11, 2015. [Online]. Available: http://dx.doi.org/10.1007/s11036-015-0575-6

[2] K. Zheng, S. Ou, J. Alonso-Zarate, M. Dohler, F. Liu, and H. Zhu, “Challenges of massive access in highly dense lte-advanced networks with machine-to-machine communications,” *Wireless Communications, IEEE*, vol. 21, no. 3, pp. 12–18, June 2014.

[3] 3GPP TR22.868 V8.0.0, “Study on Facilitating Machine to Machine Communication in 3GPP Systems,” March 2007.

[4] M. Beale, “Future Challenges in Efficiently Supporting M2M in the LTE Standards,” in *Wireless Communications and Networking Conference Workshops (WCNCW), 2012 IEEE*, April 2012, pp. 186–190.

[5] K. Zheng, F. Hu, W. Wang, W. Xiang, and M. Dohler, “Radio Resource Allocation in LTE-Advanced Cellular Networks with M2M Communications,” *Communications Magazine, IEEE*, vol. 50, no. 7, July 2012.

[6] 3GPP TR 37.868 V11.0.0, “Study on RAN Improvements for Machine-type Communications,” September 2009.

[7] T. de Andrade, C. Astudillo, and N. da Fonseca, “The impact of massive machine type communication devices on the access probability of human-to-human users in lte networks,” in *Communications (LATINCOM), 2014 IEEE Latin-America Conference on*, Nov 2014, pp. 1–6.

[8] M. Gerasimenko, V. Petrov, O. Galinina, S. Andreev, and Y. Koucheryavy, “Impact of machine-type communications on energy and delay performance of random access channel in lte-advanced,” *Transactions on Emerging Telecommunications Technologies*, vol. 24, no. 4, pp. 366–377, 2013. [Online]. Available: http://dx.doi.org/10.1002/ett.2631

[9] The ns-3 network simulator. [Online]. Available: http://www.nsnam.org/

[10] Sesia, S. and Baker, M. and Toufik, I., *LTE - The UMTS Long Term Evolution: From Theory to Practice*. Wiley, 2011, pp. 421–456.

[11] 3GPP TS 36.211 V10.4.0, “Evolved Universal Terrestrial Radio Access (E-UTRA); Physical Channels and Modulation,” December 2011.

[12] 3GPP TS 36.331 V10.5.0, “Evolved Universal Terrestrial Radio Access (E-UTRA); Radio Resource Control (RRC),” March 2012.

[13] 3GPP TS 36.321 V9.3.0, “Evolved Universal Terrestrial Radio Access (E-UTRA); Medium Access Control (MAC),” June 2010.

[14] S.-Y. Lien, K.-C. Chen, and Y. Lin, “Toward Ubiquitous Massive Accesses in 3GPP Machine-to-Machine Communications,” *Communications Magazine, IEEE*, vol. 49, no. 4, pp. 66–74, April 2011.

[15] M.-Y. Cheng, G.-Y. Lin, H.-Y. Wei, and A.-C. Hsu, “Overload Control for Machine-Type-Communications in LTE-Advanced System,” *Communications Magazine, IEEE*, vol. 50, no. 6, pp. 38–45, June 2012.

[16] A. Laya, L. Alonso, and J. Alonso-Zarate, “Is the Random Access Channel of LTE and LTE-A Suitable for M2M Communications? A Survey of Alternatives,” *Communications Surveys Tutorials, IEEE*, vol. 16, no. 1, pp. 4–16, First 2014.

[17] M. Amirijoo, P. Frenger, F. Gunnarsson, J. Moe, and K. Zetterberg, “On Self-Optimization of the Random Access Procedure in 3G Long Term Evolution,” in *Integrated Network Management-Workshops, 2009. IM ’09. IFIP/IEEE International Symposium on*, June 2009, pp. 177–184.

[18] K.-D. Lee, S. Kim, and B. Yi, “Throughput Comparison of Random Access Methods for M2M Service Over LTE Networks,” in *GLOBECOM Workshops (GC Wkshps), 2011 IEEE*, December 2011, pp. 373–377.

[19] N. K. Pratas, H. Thomsen, C. Stefanovic, and P. Popovski, “Code-Expanded Random Access for Machine-Type Communications,” in *GLOBECOM Workshops (GC Wkshps), 2012 IEEE*, December 2012, pp. 1681–1686.

[20] M. Lauridsen, A. Jensen, and P. Mogensen, “Reducing LTE Uplink Transmission Energy by Allocating Resources,” in *Vehicular Technology Conference (VTC Fall), 2011 IEEE*, September 2011, pp. 1–5.