Is the Random Access Channel of LTE and LTE-A Suitable for M2M Communications? A Survey of Alternatives

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***Abstract*—The 3GPP has raised the need to revisit the design of next generations of cellular networks in order to make them capable and efficient to provide M2M services. One of the key challenges that has been identified is the need to enhance the operation of the random access channel of LTE and LTE-A. The current mechanism to request access to the system is known to suffer from congestion and overloading in the presence of a huge number of devices. For this reason, different research groups around the globe are working towards the design of more efficient ways of managing the access to these networks in such circumstances. This paper aims to provide a survey of the alternatives that have been proposed over the last years to improve the operation of the random access channel of LTE and LTE-A. A comprehensive discussion of the different alternatives is provided, identifying strengths and weaknesses of each one of them, while drawing future trends to steer the efforts over the same shooting line. In addition, while existing literature has been focused on the performance in terms of delay, the energy efficiency of the access mechanism of LTE will play a key role in the deployment of M2M networks. For this reason, a comprehensive performance evaluation of the energy efficiency of the random access mechanism of LTE is provided in this paper. The aim of this computer-based simulation study is to set a baseline performance upon which new and more energy-efficient mechanisms can be designed in the near future.**

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

I. Introduction

MACHINE-TO-MACHINE (M2M) systems are deemed to create a revolution in our future world. Having devices connected to each other, operating in an autonomous manner, and with almost no human intervention, can facilitate the creation of unprecedented applications and new business models that cannot be foreseen today. The realization of these M2M systems poses many challenges at various disciplines of the technology, ranging from computation, sensing, or energy harvesting techniques, to communication technologies, among many others. In this paper, the focus is on the networking and communications part of M2M solutions [1].

The main mission of M2M networks is to connect, on the one side, a server running an application and processing data to make smart decisions (or to assist in the decision-making process) with, on the other side, an enormous amount of devices deployed in our world, interacting with the environment, with other machines, and with us, humans. According to the European Telecommunications Standard Institute (ETSI) architecture [2], M2M devices and applications will be connected through the network domain. This includes the access and core networks and also the M2M servers providing services and enabling applications. An example of a feasible M2M network architecture is depicted in Fig. 1, based on the cellular and M2M area networks aspects proposed by ETSI. In this architecture, it is considered that M2M devices may connect to the core networks in two different ways. One alternative is to connect through the access network, e.g., by equipping each single device with its own Subscriber Identity Module (SIM) card to have cellular connectivity. The other alternative consists in considering that M2M devices may organize themselves locally, creating M2M area networks and exploiting short-range technologies such as those based on Body Area Networks (BAN) (IEEE 802.15.6), Wireless Sensor Networks (IEEE 802.15.4 or IEEE 802.15.4e), or Local Area Networks based on Low-Power Wifi (IEEE 802.11). These M2M area networks may then get connected to the core networks through M2M gateways [3]. The architecture proposed by ETSI focuses on the service capabilities and resources needed to enable M2M applications. On a different side, the communication aspects over cellular network are covered by the 3GPP [4]. There are recent efforts done towards an unprecedented integration of short-range M2M local area networks with wide-area cellular networks, thus posing several new challenges never faced before [5]. The main goal of this combination of technologies is to exploit the strengths of both types of technology and to push the efficiency of communications to the limits [6]. Getting closer to the feasible limits is a requirement imposed by M2M systems in order to make viable a massive deployment of devices all around the globe. In order to ensure that low-cost devices can operate autonomously without human intervention, it is necessary to design them with very limited resources (memory and processing capacity) and with an ultra-low power consumption to minimize the dependence on external energy sources. Once deployed, the batteries of these devices will never be replaced, and thus their energy consumption must be close to zero. By enabling such close-to-zero power operation, new and unprecedented applications and business models can be created, having a strong impact on our vision of society for the coming years.

Manuscript received November 1, 2012; revised May 8, 2013.

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Digital Object Identifier 10.1109/SURV.2013.111313.00244

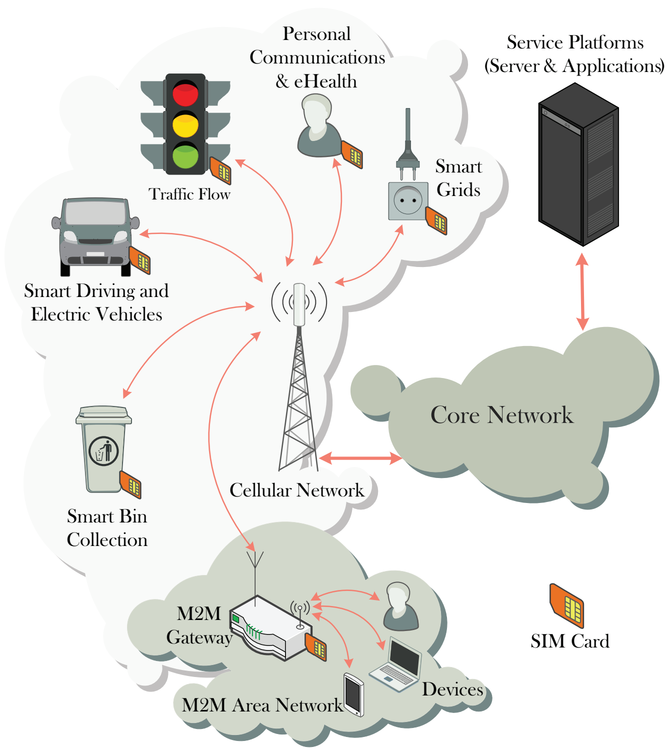

Fig. 1. Example of M2M network architecture

As it has been already raised by the 3GPP [7], getting such a high efficiency in highly dense networks poses several challenges at the cellular segment of the communication networks. Indeed, different studies have been launched over the last recent years to understand how cellular systems need to evolve to be able to provide efficient access to M2M networks [8], [9]. M2M are fundamentally different from human-based communications. This difference requires a mentality shift on the way that cellular systems are designed. A summary of some of the main differences between M2M and human-based traffic is shown in Table I.

In [7], the 3GPP identified the design of improvements for the access mechanisms of cellular systems when the number of subscribers raises up to tens of thousands per cell as a key challenge for next generations of networks. For this reason, the amount of contributions in this field has been increasing since the release of this document, leading to some overlapping studies and leaving some gaps that may need to be covered sooner or later. This is the main motivation for this paper, where a survey of recent activities on the topic is presented.

The aim of this work is to offer an in-depth and comprehensive discussion of the state of the art in order to identify the best alternatives proposed so far to improve the operation of the Random Access Channel (RACH) of LTE and LTE-A. The aim is to identify open challenges that have not been covered yet and foster some means of coordinated research in the near future. In this paper, existing alternatives are classified and compared with each other, discussing the strengths and weaknesses of all of them. One of the main conclusions that can be drawn is that most of existing proposals only focus on the degraded access delay due to a high number of accessing devices. However, very few works have focused on the energy consumption of the devices, which may be a critical factor to facilitate M2M applications. For this reason, besides surveying the state of the art in the design of improvements to the access mechanism of LTE and LTE-A, the energy efficiency of the RACH of LTE is evaluated in this paper, by means of computer simulations with the popular ns-3 [10]. Having these results as benchmark reference may enable future research efforts to improve upon the energy efficiency of the current implementation of the RACH of LTE and LTE-A.

The remainder of this paper is organized as follows: an overview of the access method of LTE and LTE-A is given in Section II, describing into detail the four-message handshake necessary to establish a connection. Section III is devoted to discuss and quantify the limits of LTE and LTE-A to handle M2M applications with very high number of devices. One of the main conclusions of the analysis of the state of the art is that there is no comprehensive performance evaluation of the RACH of LTE in terms of energy efficiency. To fill this gap, Section IV discusses the performance of the RACH of LTE in terms of energy efficiency. These results can be used as benchmark values for future research along this line. Section V contains the core part of this paper, where existing improvements of the RACH for M2M applications are classified, discussed and compared. Open lines of research are identified in this section, where the use of tree-splitting algorithms is proposed as a mean of attaining very high performance when the number of devices is very high. Finally, Section VI concludes the paper by summarizing the main findings of current state of the art and emphasizing near-future open research topics related to the RACH of LTE.

II. The Random Access Procedure of LTE

According to ETSI terminology, an M2M device is a mobile terminal capable of transmitting data autonomously. It is worth mentioning that in the 3GPP terminology, the M2M device is referred to as Machine Type Communication (MTC) Device. For the remainder of this paper, only the term ”M2M device” will be used.

An M2M device must trigger the access procedure to the base station (hereinafter eNodeB, which is the term used in LTE) in the following five situations [11]:

1) Upon initial access to the network, i.e., in the association process.
2) When receiving or transmitting new data and the M2M device is not synchronized.
3) Upon transmission of new data when no scheduling request resources are configured on the uplink control channel.
4) In the case of handover (change of associated eNodeB), to avoid a session drop.
5) After a radio link failure, in order to re-establish the connection.

In order to handle all these situations, two different forms of Random Access (RA) procedure are defined in LTE:

- **Contention-based:** where devices compete for the channel access. Since collisions can occur, this type of access is reserved for delay-tolerant access requests.

TABLE I
DIFFERENCES BETWEEN HUMAN-BASED AND M2M COMMUNICATIONS

	Machine-to-Machine	Human-based
Traffic Direction	Mainly uplink data to report sensed information. For some applications, symmetric uplink and downlink capacity is needed in order to allow for the dynamic interaction between sensors and actuators.	Mostly downlink; although uplink traffic is increasing over the last years due to interactive applications such as social networking, humans still download more than they upload.
Message Size	The size of the messages is generally very short (e.g. very few bits of the reading of a meter, or even just 1 bit to inform of the existence or absence of a given event).	The size of the messages is generally big, motivated by demanding applications such as multimedia and real-time transmissions, including video streaming.
Connection and Access Delay	Many M2M applications will be based on duty-cycling, i.e., having devices sleeping and just waking up from time to time to transmit data. For some applications, the connection delays should be very short to ensure quick access to the network when waken up.	Human-based applications tend to be very demanding once a connection has been established. However, although not desirable, longer connection delays are typically well tolerated.
Transmission Periodicity	Very wide range of alternatives. For many applications, transmissions will be very sparse in time. In addition, many applications will have known periodic patterns (e.g. programmed tasks).	Human-based data traffic is very random and asynchronous in nature. In addition, the frequent transmission of control information is required to ensure high-throughput and good delay performance.
Mobility	For many of M2M applications, mobility is not a major concern. Some applications may have no mobility at all.	Mobility management and exchange of location information are constantly required to ensure seamless connectivity and allow for roaming.
Information Priority	Some M2M applications may transmit critical information and thus require very high priority with a detailed level of granularity.	In general, there is no major differentiation between users in terms of priority, but only between applications for each user.
Amount of Devices	Higher than in human-based communications. Hundreds or thousands of devices per connection point.	Lower than in M2M. At most, hundreds of devices per connection point. Typically, tens of devices per connection point.
Security and Monitoring	M2M devices cannot raise an alert in the case of malfunctioning or tampering.	Humans can raise an alert in the case of troubleshooting or tampering.
Lifetime and Energy Efficiency	Once an M2M network has been deployed, some devices may require to operate for years or decades without maintenance.	Although annoying, humans can recharge batteries in a daily manner.

- **Contention-free:** where the eNodeB allocates specific access resources for those access requests that must have high probability of success (delay-constrained access), e.g., handover.

The focus of this paper is on contention-based RA mechanisms used for the initial association to the network, for the request of resources for transmission, and to re-establish a connection upon failure. Before discussing into detail the different existing solutions and optimizations for M2M, this section provides a general overview of the operation of the RACH of LTE.

The RACH is formed by a periodic sequence of allocated time-frequency resources, called RA slots. These slots are reserved in the uplink channel of the network for the transmission of access requests [12]. In the time domain, the duration of each RA slot depends on the format of the access requests (that will be explained later). In the frequency domain, each RA slot occupies 1.08 Mhz, which corresponds to the bandwidth of 6 Physical Resource Blocks (PRBs). The eNodeB broadcasts the periodicity of the RA slots by means of a variable referred to as the *Physical RACH (PRACH) Configuration Index*. The periodicity varies between a minimum of 1 RA slot every 2 frames, i.e., every 20ms, and a maximum of 1 RA slot per 1 subframe, i.e., every 1 ms. Fig. 2 exemplifies some RACH configurations, where colored squares represent RA slots where access requests can be transmitted by the M2M devices. LTE defines 64 possible configurations [12]. It is important to note that the RACH is allocated in the uplink and therefore, the scheduler design needs to balance the tradeoff between the amount of access opportunities to be scheduled per frame and the amount of resources available for data transmission. This can become a critical factor in M2M applications where the number of requesting devices can be very high and the available bandwidth is constrained.

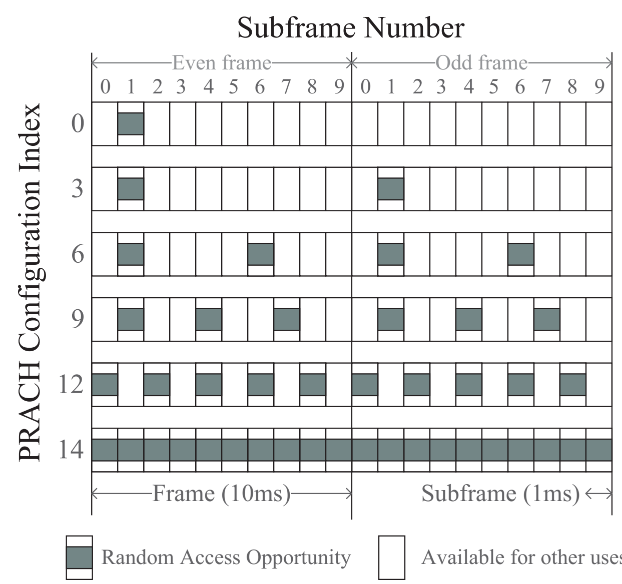

Fig. 2. Examples of the RACH Configuration Index.

The contention-based RA procedure consists of a four-message handshake between the M2M device and the eNodeB, which is described in the next subsections. An access request is completed if the four messages are successfully exchanged, as depicted in Fig. 3.

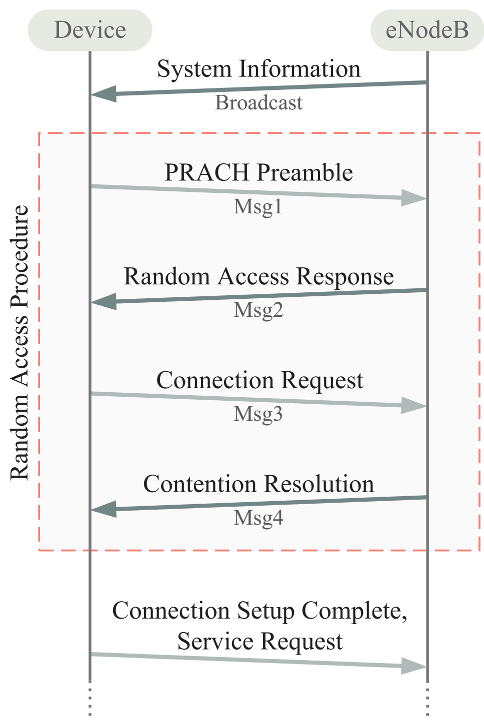

Fig. 3. Contention-Based Random Access (RA) Procedure.

A. Message 1, Preamble Transmission

Whenever an M2M device requires access to the channel, it selects the next available RA slot of the RACH to transmit an access requests. This consists of a preamble, i.e., a digital signature that the device transmits in an RA slot. There are 64 orthogonal pseudo-random preambles available for RA and the eNodeB periodically broadcast information in the downlink control channel on which preambles may be used [11]. However, the eNodeB reserves some of them for contention-free access. If two or more devices transmit the same preamble in the same RA slot, a collision occurs. Otherwise, the different preambles can be detected by the eNodeB thanks to their orthogonality. The duration of a preamble depends on the size of the cell, and can vary from 1 to 3 ms. The larger the cell-size, the longer the duration of the preamble in order to improve the reliability of reception at the cell edge. The selection of the preamble to transmit for each request is done at random (among those available for contention-based access). Exactly 3 subframes after the transmission of the preamble [13], the M2M device waits for a time window to receive a response from the eNodeB, i.e., Message 2 of the handshake. The duration of this waiting window is broadcast by the eNodeB and is defined between 2 and 10 subframes [14].

B. Message 2, Random Access Response (RAR)

For each successfully decoded preamble, the eNodeB computes an identifier, referred to as the Random Access Radio Network Temporary Identifier (RA-RNTI), which is calculated based on the RA slot where each preamble was sent [13]. Then, the eNodeB transmits a RAR through the Physical Downlink Shared Channel (PDSCH) with the following information:

- Identification of the detected preamble.
- Timing alignment instructions to synchronize uplink transmissions.
- Uplink resource allocation that will be used by the device to transmit the third message of the handshake.
- Assigned Temporary Cell Radio Network Temporary Identifier (C-RNTI).
- In the case of failure, an optional Backoff Indicator (BI) to request the devices to wait for a random period of time before retrying access [13]. This random backoff is used to reduce the probability of preamble collision, dispersing the access attempts along time.

The RAR is addressed to a specific RA-RNTI, i.e., to all the devices that transmitted a preamble on a specific RA slot. The RAR contains different subheaders associated to each detected preamble. If a device receives a RAR message addressed to the RA-RNTI associated to the RA slot where the preamble was transmitted, but it does not not contain the identifier of the used preamble, it performs a random backoff time (according to the BI parameter attached to the RAR) before scheduling another preamble transmission attempt (Message 1) [13]. If multiple devices selected the same preamble and the same RA slot, a collision will occur. The eNodeB may be able to detect the collision based on the different time of arrival. In such case, it will not provide information related to that specific preamble in the next RAR. However, if the devices are at the same distance from the eNodeB, and the two preambles have been received constructively, the collision may be undetected by the eNodeB and the same RAR information will be sent to all the devices that transmitted the same preamble in the same RA slot. This will cause a collision again in Message 3.

C. Message 3, Connection Request

The M2M device transmits a Connection Request message to the eNodeB in the resources granted in the Message 2 associated to the preamble transmitted in the selected RA slot. Message 3 is transmitted with Hybrid Automatic Retransmission Request (HARQ). For the initial access, this message conveys the device identifier (C-RNTI) and the reason for the access request. In the case of an undetected preamble collision by the eNodeB, more than one device will use the same uplink resources to transmit Message 3 and a collision will occur at the eNodeB. Therefore, no acknowledgment will be transmitted by the eNodeB and each device will retransmit Message 3 for the maximum number of retransmissions allowed before declaring access failure and scheduling a new access attempt.

D. Message 4, Contention Resolution

Upon reception of a Connection Request, the eNodeB transmits a Contention Resolution message as an answer to Message 3. A device which does not receive Message 4 declares a failure in the contention resolution and schedules a new access attempt, i.e., a new preamble transmission, starting the process over again. Each device keeps a preamble transmission counter that is increased after each unsuccessful attempt. When the counter reaches the maximum allowed value (informed as system information by the eNodeB), the network is declared unavailable by the device and a random access problem is indicated to upper layers.

III. The Limits of the RACH of LTE

The contention-based operation of the RACH is based on ALOHA-type access, i.e., transmit the request in the first available opportunity. This means that, in the case of the transmission of simultaneous access requests, the system performance may degrade due to a high probability of collision in the transmission of the preambles. Indeed, the 3GPP and organization members have released some studies regarding the capacity limits of the RA in LTE [7], [15]. In these studies, it has been considered that there is an access opportunity every 5ms and 54 out of the 64 available preambles are used for contention-based access, while the remaining 10 preambles are reserved for contention-free access (e.g. reserved for handover). Under these conditions, the system offers 200 access opportunities per second, which corresponds to a capacity of 10,800 preambles per second. Although this number may seem enough for most envisioned M2M applications, this is the absolute maximum capacity that the system tolerates in the absence of collisions. However, due to the use of ALOHA as the access protocol for the transmission of the preambles and the use of random backoffs in the case of failure, the usual system performance is much lower than this upper limit.

There are some scenarios and applications that may be compromised by such performance limits of the RACH of LTE. For example, this is the case of a power outage, after which all systems try to get connected to the network simultaneously. Another use case is the utility meters reading reports; where all the devices transmit with high correlation in reporting times. A third example is a railway bridge vibration monitoring application where, upon transit of a train along the sensor-equipped bridge, all the sensors react simultaneously and try to transmit through the network. Of course, the last case can be generalized into event-driven applications, such as fire-detection, fault alarm, security threats; this means that devices are idle for long periods of time and become active when an event is triggered. If the number of devices is known, then it is possible to design an optimum scheduling algorithm; however, if the number of devices is unknown, then random access procedures need to be used. These examples will not necessarily be infrequent. Therefore, there is a considerable amount of M2M applications that are characterized by bulk arrivals and require very high energy efficiency to ensure the long lifetime of the network.

The 3GPP is fully aware of these limitations of the RACH of LTE and is actively working in improvements to overcome congestion and overloading of the RACH when used for M2M applications [15], [16]. An extensive list of key issues and feasible system improvements are presented in [4]. In addition, different research groups around the globe have been working, and are still progressing, on identifying limitations of the RACH of LTE for M2M communications and proposing alternative solutions to avoid slowing down the penetration of M2M applications into the mass market. In an endeavor to align all the efforts in the same direction, some of the 3GPP organization members have discussed in [15], [16] three key performance indicators to evaluate the performance of the novel proposals being designed today. Additionally, based on the low power consumption requirement issue referred in [4], an energy related indicator should also be considered. This leads to the following **four** performance indicators:

1) **Access Success Probability**, defined as the probability to complete the random access procedure in the maximum number of preamble transmissions allowed. This parameter can also be represented by the blocking probability, defined as the probability that a device reaches the maximum number of transmission attempts and is unable to complete an access process.
2) **Preamble Collision Rate**, defined as the ratio between the number of preamble collisions in the same RA slot and the total number of preambles transmitted on that slot. An equivalent metric consists in measuring the average number of preamble retransmissions required to have a successful access request.
3) **Access Delay**, defined as the time elapsed between the transmission of the first preamble and the reception of Message 4 by the M2M device.
4) **Device Energy Consumption**, defined as the total energy spent in transmission and reception tasks, from the first RA attempt until the successful access to the network has been granted.

As specified by the 3GPP in [17], each application has its own requirements, and thus different performance indicators need to be considered. It may happen that a specific access technique improves the performance under very specific network conditions and traffic loads, but it performs worse when tested in different conditions. Among the wide range of degrees of freedom to define requirements, the 3GPP has already classified some key applications as: with very low mobility (or static), time-restricted applications, time tolerant applications, infrequent transmission application, and small data transmission applications.

IV. Energy Efficiency of the RACH of LTE

Energy-efficient design of wireless networks is an increasing research area [18]; energy efficiency is also a key metric for M2M applications. Nevertheless, there is a lack of efforts in trying to comprehensively understand the performance of the RACH in terms of energy efficiency when applied to M2M networks. Most of the existing work related to the RACH of LTE for M2M has been focused on measuring of the average access delay of devices. For this reason, and with the aim of setting a baseline reference study, an energy efficiency performance of the RACH of LTE is provided in this section. All the results shown in this section have been obtained through simulations with ns-3 [10]. For the purpose of the results presented in this paper, the RACH has been implemented in ns-3, within the context of the LENA project [19], and the energy model has been accordingly developed.

A. Simulator

Even though the official release of ns-3 provides LTE modules, the random access procedure had not been implemented at the time of writing of this paper. Moreover, the high amount of devices considered in M2M studies result in extremely low computational performance of the simulator. For these reasons, and for the purpose of this paper, new modules to specifically

TABLE II
SIMULATION PARAMETERS

Parameter	Simulated Values
PRACH Configuration Index [a]	0, 3, 6, 9
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. 2 for the number of access resources per frame.
[b] Refer to the 3GPP TS 36.321 [13] for all the possible values.
[c] Refer to the 3GPP TS 36.331 [14] for all the possible values.

simulate the RACH of LTE in Frequency Division Duplex (FDD) mode have been developed.

B. System Setup

A cellular LTE network is considered, where a number of M2M devices are cell-synchronized at the beginning of the simulation and they have already received all the configuration parameters related to the RA procedure. Control signaling transmissions related to the system information are out of the scope of this simulator. In order to understand the limits of the RACH of LTE, simulations have been performed with more than 1,000 devices that need to access the network and attempt access simultaneously.

According to the LTE standard, the probability to detect a collision of the same preamble when transmitted by two devices on the same RA slot depends majorly on the relative transmission delay between the colliding devices, i.e., in those cases where the two preambles are received with very little time difference, the eNodeB will probably decode the overlapping preambles as a single preamble with multipath components. However, this probability is not considered by the 3GPP in [7] and it is proper to evaluate the performance assuming that the eNodeB will not be able to decode any of the simultaneous transmissions of the same preamble. Therefore, it will not send the RAR for those preambles. The parameters in Table II were simulated to understand the actual behavior of the network. The number of available preambles corresponds to the signatures available for the contention-based procedure. The parameter *preambleTransMax* corresponds 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 wait to receive Message 4 (contention resolution) after sending Message 3.

For the energy consumption parameters on the device, the maximum transmission power for a LTE class 3 user equipment has been considered, i.e., 23dBm. Moreover, and based on the study presented in [20], the total power consumption on the device is 2W, taking into account the energy consumption generated by the RF chain, including power amplifiers, based band, circuitry consumption and the transmitted power. This performance evaluation only focuses on the energy efficiency of the devices. If a device reaches the maximum number of preamble transmissions without gaining access to the network, it is blocked by the network. The time elapsed during the access attempts and the energy consumed by devices blocked by the network are not considered for the average calculations of the delay and energy consumption results presented in

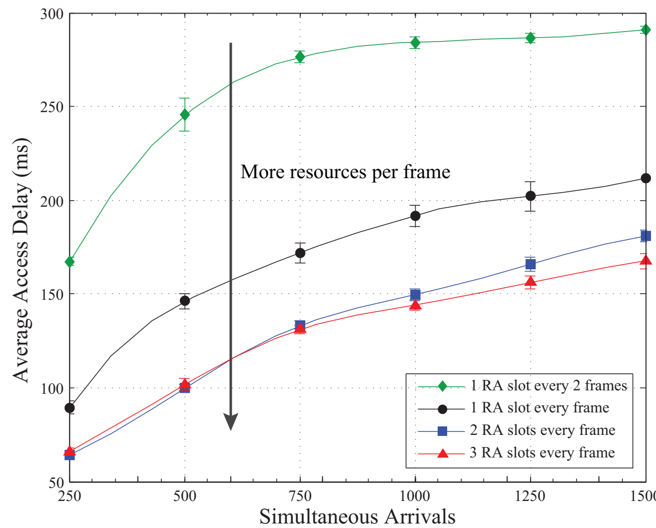

Fig. 4. Average access delay per M2M device with a maximum number of preamble retransmissions = 10.

this study. Thus, the average access delay results should be regarded in close relation with the blocking probability to fully understand the system evaluation.

C. Results

Two sets of evaluation have been carried out; one to evaluate different configurations of the PRACH Configuration Index and the other to evaluate different values of the *preambleTransMax* parameter. In both cases, the objective is to understand the behavior of the RACH of LTE when the number of preambles sent on a specific RA slot increases and, then, the following reattempts are scattered due to the BI (backoff indicator). In order to achieve this goal, a fixed initial number of simultaneous arrivals to a RA slot are considered. The performance of the mechanism to resolve the contention is evaluated only for these arrivals, including their subsequent preamble retransmissions.

On the first evaluation, the maximum number of preamble transmissions per device has been fixed to 10, and the PRACH Configuration Index takes several values: 0, 3, 6, and 9. Recall that the greater this value, the more RA slots are available per time frame.

The results in terms of average access delay are shown in Fig. 4. As expected, the average access delay decreases when more RA slots are allocated per frame, i.e., when there are more channel access opportunities. In addition, the access delay tends to stabilize to a constant value when the number of simultaneous arrivals increases. However, as it can be seen in Fig. 5, there is an increasing blocking probability when the number of simultaneous arrivals increases, i.e., for higher number of simultaneous arrivals, more devices will fail all the contention attempts and will not get access to the network. Of course, even though the delay increases when there are more simultaneous arrivals, the probability that a device cannot connect to the system is reduced if more access opportunities are allocated per frame.

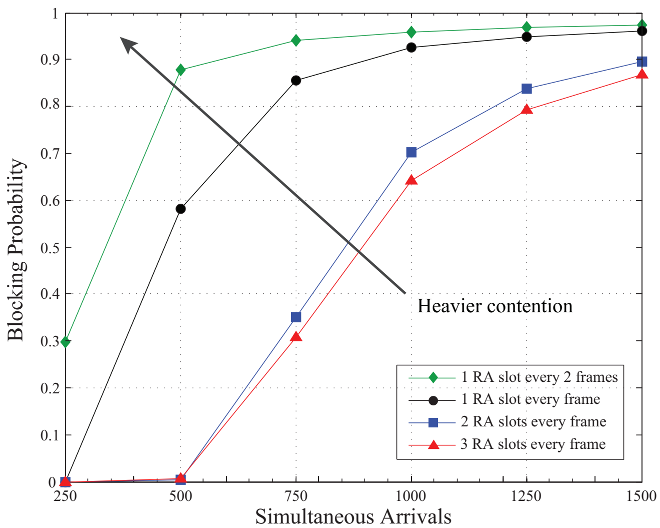

Fig. 5. Blocking probability with a maximum number of preamble retransmissions = 10.

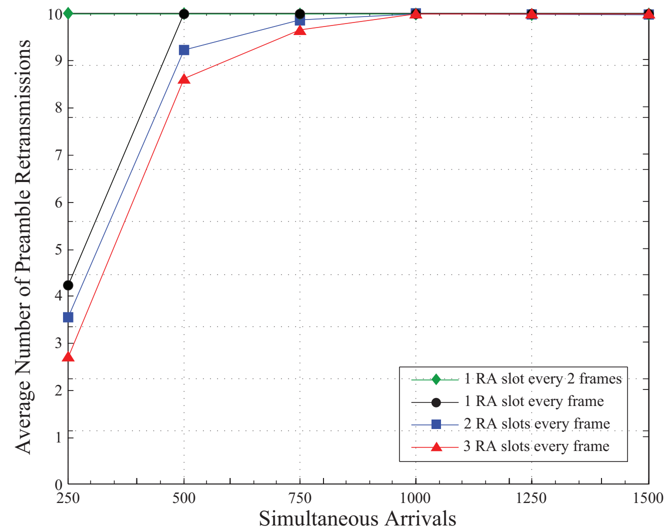

Fig. 7. Average number of preamble retransmissions with a maximum number of preamble retransmissions = 10.

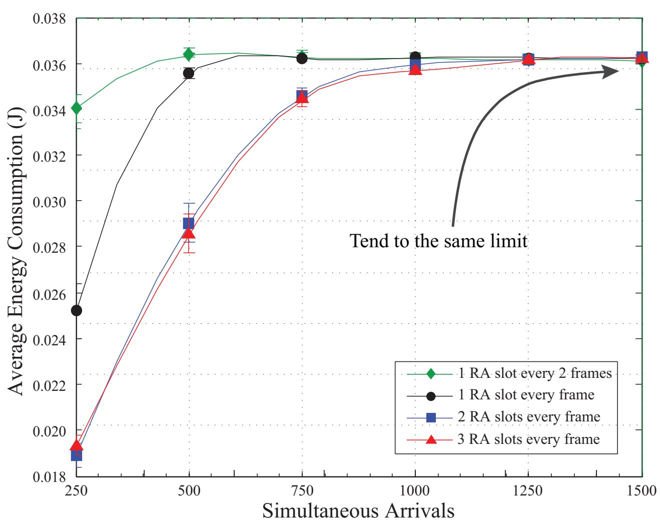

Fig. 6. Average energy consumption M2M device with a maximum number of preamble retransmissions = 10.

The energy consumption associated to the access procedure is shown in Fig. 6. It can be seen how the performance quickly degrades as the number of simultaneous arrivals increases. In addition, the lower the value of the PRACH Configuration Index, i.e., the number of RA slots per frame, the higher the energy consumption of the devices due to the heavier contention. In addition, it is interesting to see that the energy consumption tends to a common value regardless of the amount of RA slots per frame as the amount of simultaneous arrivals increases. This is an artifact of limiting the maximum number of retransmission attempts. To better understand this, the average number of preamble retransmissions is shown in Fig. 7. It can be seen that the maximum number of transmission attempts is quickly reached as the number of simultaneous arrivals increases, and independently of the PRACH Configuration Index.

For the second evaluation study, the PRACH Configuration Index has been fixed to 6, i.e., 2 RA slots per frame, and different values for the maximum number of preamble transmission attempts (*preambleTransMax*) have been evaluated (3, 10, 15 and 50).

The results in terms of average access delay are shown in Fig. 8. The access delay increases as the maximum number of retransmission attempts increases as well. Indeed, for 50 maximum retransmissions, the performance of the RACH is almost 4 times slower than for the other configurations when the simultaneous number of arrivals reaches 1,400; when having more retransmission opportunities, the devices remain in contention for much longer. Fig. 9 presents the results for the blocking probability and shows how the performance degrades quickly as the maximum number of retransmission attempts is reduced. Again, there is a clear tradeoff between the average access delay and the blocking probability. The final tuning of the access parameters will thus strongly depend on the specific application.

In terms of energy efficiency, the results are shown in Fig. 10. When the number of simultaneous arrivals is relatively small, all the configurations perform similarly, offering very efficient access in energy terms. However, the energy quickly increases with the number of simultaneous arrivals, due to a higher probability of collision; this leads to a greater average number of required retransmissions, as shown in Fig. 11.

Therefore, all these results show that the performance of the RACH of LTE in terms of average access delay, blocking probability, and energy consumption is very dependent on the application, which characterizes the average number of simultaneous arrivals, and not the system configuration, i.e., the amount of resources allocated for access. Of course, adding more resources to the RACH improves its performance. Unfortunately, over-provisioning the RACH of LTE is not the optimal solution since the more resources allocated to the RACH imply less resources available for data transmissions. The quantification of this tradeoff remains as an interesting open line for research.

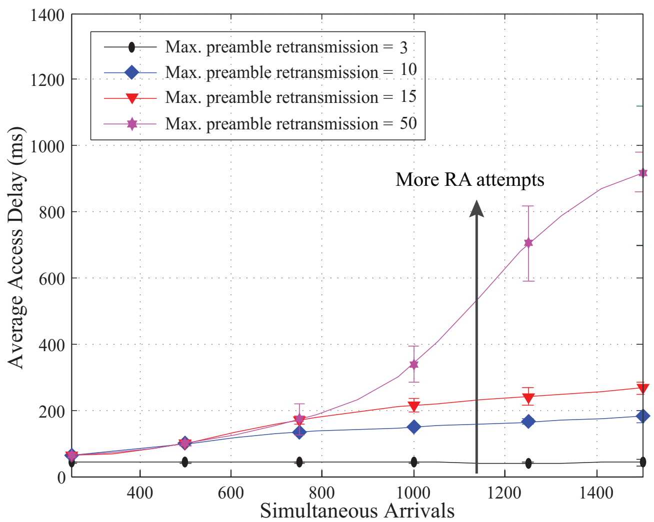

Fig. 8. Average access delay per M2M device with 2 RA slots per frame.

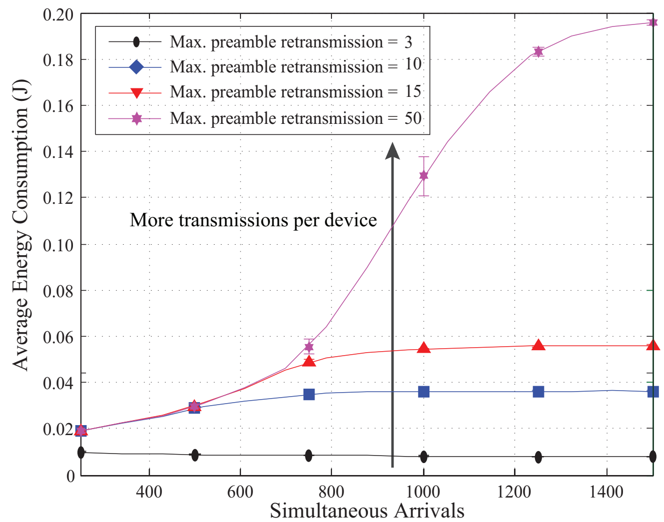

Fig. 10. Average energy consumption M2M device with 2 RA slots per frame.

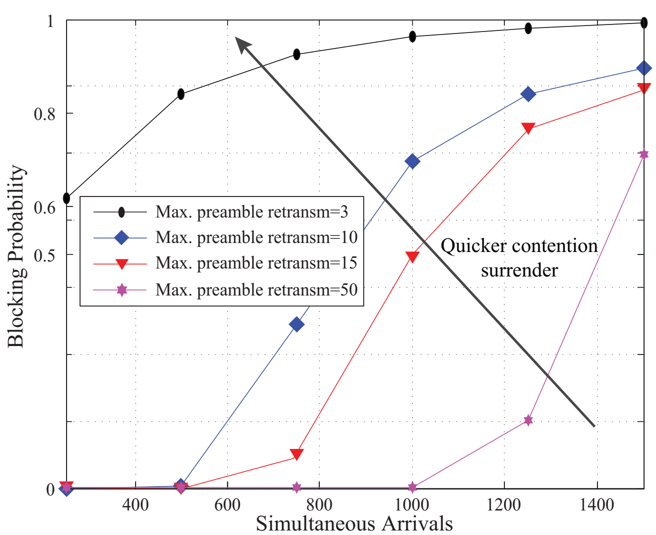

Fig. 9. Blocking probability with 2 RA slots per frame.

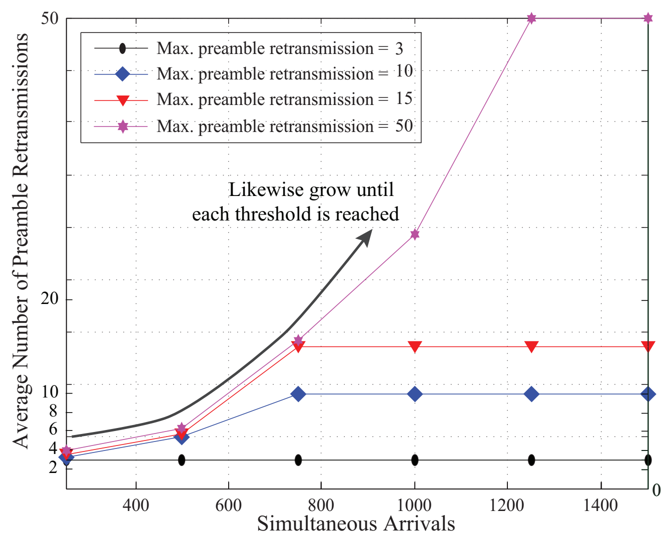

Fig. 11. Average number of preamble retransmissions with 2 RA slots per frame.

In the next section, existing proposals to improve the performance of the RACH considering different application requirements are described and discussed.

V. Random Access Improvements

Over the last years, the definition of new mechanisms to overcome the impending access under-provision of LTE for event-triggered access requests has become an active research field [5]. However, most of the available solutions are based on the initial proposals compiled by the 3GPP in [7] and further discussed in [21], [22].

Fig. 12 shows a classification of existing solutions according to their specific approach. The scope and limitations of these works are thoroughly compared in Table III. The aim of this section is to discuss this proposed classification and to provide an in-depth analysis of the strengths and weaknesses, synergies and discrepancies of the solutions. Open research challenges are also identified.

A. Optimized MAC

Aiming at applications where M2M devices transmit very small amounts of data, the authors in [30] suggest removing the need to connect to the network to transmit data. The key idea is to transmit data embedded into the access process by attaching data to either the preambles, i.e., Message 1, or into Message 3 of the RA process. While the solution based on the preambles is not very scalable due to the limited amount of available preambles, the transmission of data into Message 3 seems a very interesting and straightforward idea. These options may reduce significantly the amount of control information exchanged between M2M devices and the eNodeB, but at the expense of impeding any mobility or paging capabilities. Furthermore, the authors in [30] only provide the ideas, without performing any thorough mathematical or computational analysis to provide results, and there are no subsequent publication indicating the continuation of this effort.

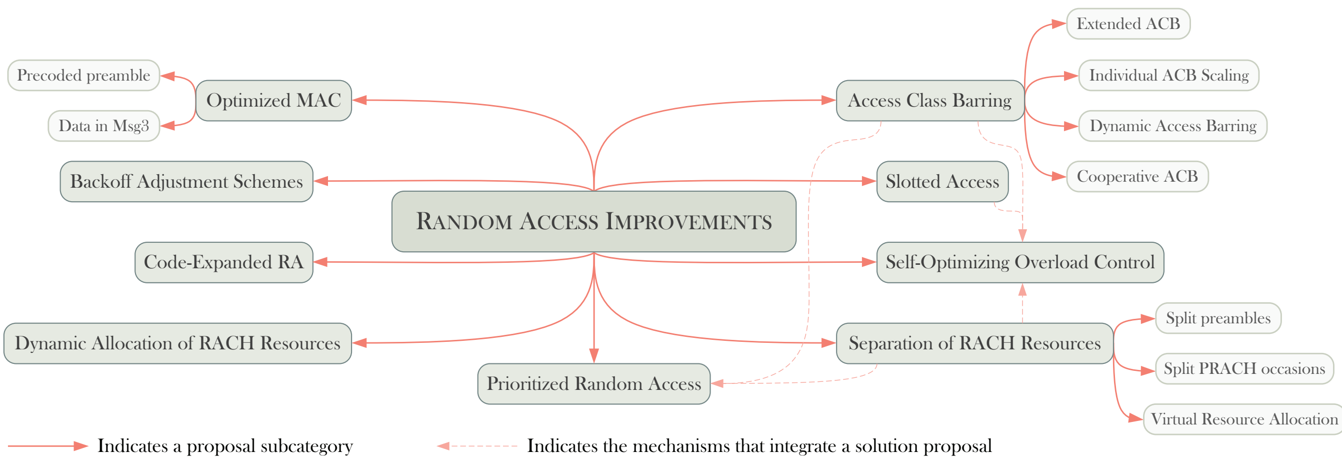

Fig. 12. Diagram of proposals to overcome random access overload.

TABLE III
COMPARISON OF PROPOSALS

Solution			Metrics			Validation			Traffic		
Type	Sub-type	Reference	Energy	Delay	Throughput	Testbed	Simulation	Theory	M2M	H2H	Number of devices**
Optimized MAC	Precoded Preamble	[23]		✓	✓						-
	Data in Msg3	[23]		✓	✓						-
Access Class Barring schemes	Individual ACB Scaling	[7]		✓							-
	Extended Access Barring	[24]		✓			✓		✓	✓	30000
		[25]		✓			✓		✓	✓	37396
	Dynamic Access Barring*	[25]		✓			✓		✓	✓	37396
	Cooperative ACB	[26]		✓	✓		✓	✓	✓		50000
Separation of RA Resources	Split PRACH occasions	[7]		✓							-
	Split Preambles	[24]		✓			✓		✓		30000
		[23]			✓			✓	✓	✓	100 per min
	Virtual Resource Allocation*	[25]		✓			✓		✓	✓	37396
Other Solutions	Dynamic Allocation of RACH Resources	[24]		✓			✓		✓		30000
	Backoff Adjustment Schemes	[24]		✓			✓		✓		30000
		[27]		✓	✓		✓	✓	✓		-
	Slotted access	[7]		✓							-
	Prioritized Random Access	[25]		✓			✓		✓	✓	37396
	Self-Optimizing Overload Control	[28]		✓							-
	Code-Expanded RA	[29]		✓	✓			✓	✓		1200

* Evaluated as part of the Prioritized Random Access proposal.
** Approximation, as some studies present their results based on arrival rates and other do not specify the total number devices in the H2H share.

B. Access Class Barring (ACB)

ACB is actually specified as a mechanism to control the access to the air interface in LTE and LTE-A [14]. 16 different classes are defined and some of them are reserved for high-priority special uses, such as emergency services, security services and public utilities. In the case of network overload, the eNodeB transmits a set of parameters related to ACB as part of the system information; this includes a probability factor and a barring timer for the different classes; additionally, it transmits a set of barring bits for the high-priority cases.

Devices which attempt to access the network will draw a random number; if this number is lower than the probability factor, the device is able to attempt an access. Otherwise, the access is barred and the device performs a random backoff time (according to the barring timer value broadcast by the eNodeB) before scheduling the preamble transmission. For high-priority access classes, a string of bits indicates whether the access is being barred or not.

The throughput of the RACH can be improved with this mechanism. However, in the case of serious congestion, the probability factor might be set to a very restrictive value, i.e., dispersing access attempts over time and therefore, increasing the access delay. Several authors have worked into this idea to adapt it for M2M scenarios. As specified by the 3GPP in [7], a different number of required classes could be defined, depending on the granularity of the control needed among the M2M devices. The main contributions can be summarized as:

1) Individual ACB Scaling: in order to achieve more control granularity, the network shall signal how individual devices or groups of devices will scale the barring parameters. This method is proposed in [7], but there is no indication of any further study regarding this solution.
2) Extended Access Barring (EAB): the basic idea is that devices that belong to delay-tolerant applications are not permitted to access the network in the case of

congestion, leaving the contention for devices that are delay-constrained; this method has been proposed by the 3GPP as the most feasible baseline solution and is adopted for radio access overload control [7]. Simulation results have been provided in [24], [25], where different barring factors are given to M2M devices. This scheme slightly improves the access success probability, but the access delay of M2M devices is severely increased.
3) Dynamic Access Barring: in this method, the eNodeB continuously monitors the loading state of the network in order to control the number of preamble transmissions on each RA slot. In the case of high traffic load, new arrivals from M2M devices are delayed until the conditions improve. This scheme has not been evaluated as a standalone solution. Instead, it corresponds to an integral part of the Prioritized Random Access proposal [25]. This solution is not compatible with delay-constrained applications, such as critical alarms, because their access cannot be postponed.
4) Cooperative ACB: this solution takes advantage of the high probability that M2M devices are in the coverage area of more than one cell (overlapping macro, pico, or femto-cells). In order to optimize the overall performance of the network, all the ACB parameters from every eNodeB are mutually optimized based on congestions levels at each eNodeB [26]. The impact on the air interface is minimal, as it only uses the probability factor parameters. This approach substantially reduces the delay, achieving 30% of improvement in comparison to the basic ACB scheme. However, this mechanism is only valid when M2M devices are located in the coverage area of more than one cell.

The main drawback of ACB mechanisms is the increased delay that some devices may experience. In addition, these schemes are not well-suited for event-driven applications where congestion can arise in a very short period of time. Even though the 3GPP considers EAB as the solution for overload control [7], other studies found in the literature coincide in suggesting that ACB mechanisms should not be considered as stand-alone solutions to overcome network congestion problems in M2M networks [21], [22].

C. Separation of RA Resources

This set of improvements can be also referred to as *Virtual Resource Allocation* [25]. The separation of resources can be achieved either by splitting the available preambles into Human-to-Human (H2H) and M2M subsets or by allocating different RA slots to H2H and M2M devices [7], [24]. Some studies have considered that H2H devices should be able to use all the resources and only the M2M devices will be restricted to the pre-defined subsets [23]. The separation of resources might help reducing the negative impact on non-M2M devices. Nevertheless, these solutions alone provide limited benefits, because the available resources are severely reduced for M2M devices and the performance tends to be worse under high M2M traffic load.

D. Other solutions

There can be found in the literature other solutions that cannot be classified into any specific group. Either because they combine some of the previous mechanisms, or because they propose some techniques that hold nothing in common with other proposals. These other proposals are:

1) Dynamic Allocation of RACH Resources: in this scheme, the network can allocate additional RA slots to M2M devices in the case of congestion, in order to cope with the additional load. Simulations results presented by the 3GPP in [24] show that this additional allocation can solve most of the cases of access congestion, providing high efficiency to the system. Therefore, the study concludes that allocating additional RA slots for M2M devices should be considered as the basic solution to solve the access overload. However, it is important to bear in mind that this allocation will occupy resources originally intended for data transmission. Therefore, it is not an effective improvement for high traffic load cases, as there is a tradeoff between the amount of access opportunities and the amount of resources available for data transmission.
2) Backoff Adjustment Schemes: for this improvement, different backoff timers are used to delay access attempts, assigning specific values to M2M devices. Although these schemes can provide some improvements for low congestion cases [24], [27], they are not sufficient to cope with peak congestion levels. The main reason for this is the fact that the average access delay will be severely degraded without substantially improving the access probability.
3) Slotted Access: in this scheme, dedicated RA slots are defined for each M2M device to access the network. M2M devices calculate their corresponding RA slot based on their identity and a parameter called RA cycle and broadcast by the eNodeB, which indicates the allocated RA slot periodicity [7]. The main drawback of this approach is the fact that in order to allocate a dedicated RA slot per device in the case of access overload, it is necessary to assign large RA cycles, leading to delays that many M2M applications will not tolerate. Nevertheless, this solution has been considered as an integral part of the Self-Optimizing Overload Control mechanism [28], which will be later explained.
4) Prioritized Random Access: in this proposal, the solution is based on the integration of two mechanisms: Virtual Resource Allocation and Dynamic Access Barring [25]. Virtual Resource Allocation is used to separate the RA resources in five different classes, namely: *i)* H2H, *ii)* low priority, *iii)* high priority, *iv)* scheduled, and *v)* emergency calls. M2M devices can only use the subset of resources according to their class. Dynamic Access Barring is used to bar new arrivals from M2M devices in the case of high traffic load. Simulation-based performance results are presented in [25] for different applications, i.e., voice calls, fleet management, hospital care, smart meters and seismic alarms. These results are compared with the EAB scheme, concluding that

this solution is able to achieve better performance in comparison to other EAB methods in terms of both success probability and average access delay.

5) Self-Optimizing Overload Control (SOOC): the work presented in [28] proposes a self-optimizing mechanism that can configure the RA resources according to the load condition. The scheme is comprised of an adaptive integration of other solutions, including Separation of RACH Resources, ACB schemes, and slotted-access scheme. Two classes are added to the LTE-A ACB scheme for M2M devices, i.e., low priority and high priority. If a device is not able to get an access grant on the first attempt, it enters in overloaded control mode; this means that for the next attempt it will perform an ACB scheme before transmitting the next preamble. An important feature of SOOC is that it implements a mechanism to collect information for overload monitoring and adjusts RA resources. When a device receives a RAR, it sends the number of retransmitted preambles to the eNodeB within Message 3. With this information, the eNodeB can determine the congestion level of the RACH. Based on the congestion level, the eNodeB varies the RA slot provisioning. If the number of RA slots reaches a maximum available limit, then the eNodeB temporarily restricts the access to the lowest priority M2M class, until the overload conditions improve. This solution might be capable of handling high traffic loads. Unfortunately, the work presented in [28] only presents a theoretical analysis and no further results have been provided by means of either simulation or real implementation.

6) Code-Expanded RA: in [29], it is proposed a mechanism by which RA slots are assembled in groups referred to as virtual frames and the access is performed over these virtual groups. The mechanism consists in transmitting codewords instead of preambles. A codeword is created when an M2M device transmits one preamble on each of the RA slots that composes the virtual frame. This allows expanding the number of contention resources and, therefore, reducing the collisions. The performance of this proposal has been evaluated through computer-based simulations and the results show that it is especially suited for high traffic loads. The only noticeable drawback of this proposal is its associated energy consumption. Note that, for each attempt, the device must perform more than one preamble transmission per each access attempt.

E. A Promising Approach: Distributed Queuing

All the previously presented proposals are aimed to enhance the RACH performance considering the possible massive access situations that M2M communications may bring about. However, to some extent, all of them are finally based on ALOHA-like mechanisms. This fact generates a certain level of instability, inefficiency, and uncertainty in the access outcome. There exist other approaches that can tackle these issues, in a more efficient manner. In particular, Campbell and Xu [31] proposed a MAC protocol whose high performance is completely independent of the number of nodes/users sharing a common channel. This is specially fitted to M2M communications, where high density of uncoordinated devices may put a really tight challenge into the access to the system. Since the very first proposal [31], several studies have analyzed the performance of the protocol for a wide set of study case scenarios [32], [33]. All of them demonstrate the stability of its performance and the near optimum behavior in terms of channel utilization, access delay, and energy consumption for all system layouts. Furthermore, several extensions and adaptations for different wireless systems have been also proposed in the last years such as for 3G networks [34], WLAN [35], mobile ad-hoc networks [36] and BANs [37]. In all these cases, the protocol has shown its great performance for any mixture of traffic patterns, loads, and Quality of Service (QoS) requirements.

The key element of the protocol is the so-called Distributed Queuing (DQ) paradigm. In a nutshell, DQ is based on the combination of a m-ary tree splitting algorithm with a smart set of simple rules that allow organizing every device in one out of two virtual queues. These queues actually do not exist physically, but they are logically distributed queues maintained by all the devices in the network. These queues have a partial representation at each device using only four integer counters to represent the total amount of devices in each queue, and the current position of the device in each queue, respectively. The appropriate update of the values of these counters, performed in a distributed manner and autonomously, allows each device to know the exact state of the queues, including their own position within them. In this way, the devices know when their turn to transmit has arrived, indirectly acquiring the access grant for transmission while completely avoiding collisions.

The smart distributed scheduling of the queues permits having almost full utilization of the channel regardless of its capacity, the number of the transmitting nodes, and the traffic pattern. Due to the rules of DQ, it behaves as a random access method for low traffic loads, and it switches smoothly and seamlessly to a reservation access method as the traffic load increases. These dynamics of DQ makes it an ideal candidate to be considered for the RACH of LTE and LTE-A under the presence of a high number of competing devices. These features perfectly match the requirements of M2M communications, especially for massive access when a high number of devices must share the same channel resources.

Some ongoing research efforts are being carried out by the research groups led by Luis Alonso at [38] and Jesus Alonso-Zarate at [39] in order to propose different ways of applying DQ ideas within LTE and LTE-A systems. The main focus of these works is to optimize the energy consumption of the RACH in the presence of a high number of devices.

VI. CONCLUSIONS

According to the conclusions of different technical studies from the 3GPP and organization members, the random access channel of LTE and LTE-A networks is prone to congestion in M2M communications scenarios, when the number of simultaneous M2M devices attempting to access the system is very high. For this reason, research groups around the globe have attempted to design improvements to the random access operation of these systems over the recent years in order to make it suitable for M2M applications, where the number of devices can be orders of magnitude higher than in any unprecedented human-based application.

In this paper, baseline performance values of the RACH of LTE in terms of energy efficiency have been presented. These results show that the configuration of the RACH can have a great impact into the performance of the network. Indeed, the RACH of LTE can be capable of handling a huge number of devices, at the cost of either long access delays or high energy consumption.

A comprehensive survey and comparison of the existing research proposals has been presented. Existing solutions have been classified according to their approach to solve the congestion problem; some proposals suggest optimizations on the MAC layer, others assign separate resources for M2M and H2H traffic, some others distribute the arrivals along time resorting to random counters, and some other proposals combine all these concepts to improve the performance of the random access channel.

All in all, the main relevant conclusion that can be drawn is that the majority of existing proposals target a reduction of the average access delay in highly dense networks, i.e., the time that the M2M devices need to get connected to the network. Different works have covered the requirements of diverse applications, and thus the understanding of the limitation of the access channel of LTE and LTE-A can be considered well known at this point in time. In a nutshell, the current access mechanism is not capable of managing the access request from thousands of devices for time-constrained applications and, therefore, further improvements are required.

In addition, and somehow surprisingly, very few works have aimed at the optimization of the energy consumption associated to the random access process and moreover, solutions are based in ALOHA as the access protocol and thus continue suffer from congestion. Therefore, the design of new techniques to improve the energy efficiency and performance of the random access procedure remains an open challenge. In this sense, this paper suggests to use contention resolution techniques based on tree-splitting algorithms to balance the average access delay and the energy consumption. These protocols perform independently of the number of competing devices and their energy efficiency can surpass the capabilities of current random access schemes used in LTE and LTE-A.

Besides, a fundamental study of the capacity of the RACH of LTE constitutes a very interesting challenge as an open field for further research. Thus, it is still necessary to quantify and better understand the tradeoff between over-provisioning the RACH of LTE to improve the access performance, and the impact on the available resources for data transmissions.

The work presented in this paper analyzes and compares the strengths and weaknesses among proposed improvements for the RACH of LTE and many lessons can be drawn from it. The main message is that any proposed solution should be evaluated by means of the key performance indicators described in the paper, which have been pointed out by the different techniques that can be found in the literature. Also, it is necessary to bear in mind that one of the main targets of the 3GPP is to redesign the networks for M2M applications without jeopardizing the performance of human-based applications. In the end, both humans and machines will live together.

ACKNOWLEDGMENT

This work has been funded by the Catalan Government under grant 2009-SGR-940, research projects GEOCOM (TEC2011-27723-C02-01), CO2GREEN (TEC2010-20823), NEWCOM # (FP7-318306) and the fellowship program between *SENER I.S.* and *Universitat Politècnica de Catalunya*.

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