Challenges of Massive Access in Highly Dense LTE-Advanced Networks with Machine-to-Machine Communications

Kan Zheng, Suling Ou, Jesus Alonso-Zarate, Mischa Dohler, Fei Liu, and Hua Zhu

Abstract

Machine-to-machine wireless systems are being standardized to provide ubiquitous connectivity between machines without the need for human intervention. A natural concern of cellular operators and service providers is the impact that these machine type communications will have on current human type communications. Given the exponential growth of machine type communication traffic, it is of utmost importance to ensure that current voice and data traffic is not jeopardized. This article investigates the limits of machine type communication traffic coexisting with human communication traffic in LTE-A networks, such that human customer churn is minimized. We show that under proper design, the outage probability of human communication is marginally impacted whilst duty cycle and access delay of machine type communications are reasonably bounded to ensure viable M2M operations.

Introduction

Current market penetration and recent predictions confirm that machine-to-machine (M2M) system deployments are increasing exponentially. This is driven by the needs of industries to automate their real-time monitoring and control processes, and the increasing popularity of smart applications to improve human well being. Examples are the automotive industry, which utilizes sensors to monitor the status of critical car components; the smart grid industry, which monitors critical points in the power transportation and distribution networks; and the smart city market, which provides innovative services to citizens by using real-time sensory data from the streets.

Capitalizing on the potential and applicability of M2M, various industrial standardization bodies have commenced embedding the unique needs of M2M systems into legacy wireless communication systems. This is the case of the IEEE and the Internet Engineering Task Force (IETF), which are defining standards suitable for M2M applications based on short- and mid-range technologies such as IEEE 802.11 or the IEEE 802.15.4x, with different amendments for low-power industrial and smart applications (e.g., smart cities and smart grids). However, such networks suffer from some limitations, such as the use of shared exempt frequency channels (prone to interference) and limited radio coverage, which compromises the mass deployment of M2M services, but are easily overcome by cellular networks. Indeed, cellular networks constitute a very interesting alternative to providing M2M coverage. The fact that the infrastructure is already installed enables a fast and low-cost deployment of M2M services in a very short time, also providing a simple network topology based on one-hop communications.

Unfortunately, current third generation (3G) and Long Term Evolution (LTE) cellular networks were not designed for M2M traffic. Instead, they were mainly designed to support human-based services such as voice and web browsing, and bandwidth demanding services such as video streaming. Therefore, the network architecture needs to be improved to accommodate new M2M service requirements without sacrificing the quality of human-based services. For example, among others, M2M data traffic is mainly uplink, while current data traffic in human-based applications is mainly downlink; the amount of data per device is very small (e.g., only a few bits of information per transaction); the number of envisioned devices in the network is very high, orders of magnitude above that of humans; also, ultra-high energy efficiency is necessary to ensure the longlife-time of networks once deployed to make sure that M2M deployments can be autonomous and do not require frequent human intervention.

For these reasons, leading standardization bodies, such as the International Telecommunications Union (ITU), the European Telecommunications Standards Institute (ETSI), the Third Generation Partnership Project (3GPP), the Telecommunications Industry Association (TIA), and the Chinese Communications Standard

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Association (CCSA), and global initiatives such as OneM2M, have commenced work on satisfying these and other constraints while not jeopardizing current cellular system usage for human-based applications. For example, in 2009 ETSI launched an M2M technical committee to actively look into architectural design, while 3GPP is incorporating M2M through its machine type communications (MTC) designs, coexisting with human type communications (HTC). In all cases, one of the main objectives of these organizations is to identify open challenges where efficient solutions can be proposed.

Among others, the random access channel (RACH) of LTE (and LTE-Advanced, LTE-A, which is essentially the same at the RACH level) has been identified as a key area where improvements for MTC traffic are needed. The fact that the RACH of LTE is still based on a random access mechanism turns it into a potential bottleneck for the performance of cellular networks if the number of MTC devices grows [1]. For this reason, the RACH of LTE has attracted lots of attention from the research community. However, with the exception of [2], research related to the coexistence of MTC and HTC devices, which is the expected modus operandi in practical networks, has been scarce to date. This is the motivation for the work presented in this article, where we address this uncertainty and show, via computer-based simulations, that the current operation of the RACH of LTE is suitable for the projected M2M traffic requirements as long as appropriate priority mechanisms are applied to balance MTC and HTC traffic. A major challenge has been to ensure that designed coexistence mechanisms are 3GPP-compliant and thus practically viable.

To this end, we overview latest 3GPP standardization activities and describe in sufficient detail the access method of the RACH of LTE/LTE-A. We introduce two access methods based on weighting the access priority of HTC and MTC according to the service types, and show that the impact of MTC onto HTC heavily depends on the access method of choice. Based on these results, we propose two improved access mechanisms to reduce the impact of MTC onto HTC. We have then simulated the RACH of LTE with the proposed schemes and thoroughly discuss the numerical results. Simulations confirm that, under suitable design, the impact of MTC onto HTC can remain almost negligible, even for a very large number of M2M devices in the same cellular coverage cell. Furthermore, we show that relevant performance metrics, such as average access delay, energy consumption, and outage probability (i.e., probability of not getting access to the network) remain reasonably bounded to facilitate delay-critical M2M applications. Finally, conclusions are drawn and future challenges outlined later.

3GPP LTE-A MTC Standard and RACH Procedures

3GPP is focused on the definition of technical requirements and functional specifications aimed at two different objectives;

- To adapt existing technologies (2G and 3G networks) to support MTC traffic
- To optimize the design of future networks (LTE and LTE-A) to provide efficient MTC services [3]

From Release 10 onward, 3GPP started to work in the design of a suitable core network architecture (from the application to the devices), services, specific signaling reduction and optimization at the radio access network (RAN) for MTC services, including mechanisms for identifying and addressing devices, device triggering, and usage of SMS over packet switching connections for data transfer. For Releases 12 and 13, the work is mainly focused on optimization of transmissions for small data packets, triggering of devices with different priorities, higher energy efficiency for terminals, and group management functions. The addition of new interfaces in the network architecture is also being designed to decouple MTC servers from the overall network functional blocks to ensure that HTC and MTC traffic can be handled simultaneously in an efficient manner. 3GPP takes into account the specific requirements posed by a huge variety of different MTC services, which, besides posing very diverse quality of service (QoS) requirements, may also need to handle a huge amount of devices, provide ultra-low energy consumption and low-cost solutions, and facilitate the coexistence of both MTC and HTC applications.

The work presented in this article focuses on the RACH of the LTE/LTE-A standards and contributes to the need to evaluate the impact of MTC traffic on the requirements of HTC users. According to the ETSI M2M architecture and the network improvements for MTC developed by the 3GPP [4, 5], exemplified in Fig. 1, three types of MTC access methods are defined.

Direct access: An MTC can directly access an evolved NodeB (eNB) in cellular networks without any intermediate device. This type of communication is similar to that of a regular user equipment device (UE). Even though this is the simplest access method, it may lead to traffic congestion in the presence of a huge number of MTC devices in the network if the amount of access resources is not enough.

Gateway access: MTC devices can obtain cellular connectivity through M2M gateways. An M2M gateway is a dedicated device with different functionalities from those of regular MTC devices. M2M gateways relay data transmissions between the eNB and a group of MTC devices, but do not generate their own data traffic.

Coordinator access: In some cases, MTCs can also play the role of coordinators to help their neighbor MTC devices access the network by providing two-hop communication. Adjacent MTC devices can be grouped before transmission in order to reduce redundant signaling and avoid congestion. One MTC device in the group can be assigned the coordinator role to communicate with the eNB, thus acting as a temporary M2M gateway to transmit the data from all the members of its group. This access method can reduce the overall power consumption of all MTCs and thus extend the service life of the battery-constrained devices.

Unfortunately, 3G and LTE networks were not designed for M2M traffic. Instead, they were mainly designed to support human-based services such as voice and web browsing, and bandwidth demanding services such as video streaming.

We propose splitting the devices of a network into two groups (i.e., one with all the MTC devices and another one with all the HTC devices). Then we study two backward-compatible ways of providing each of these groups access priority against the other group.

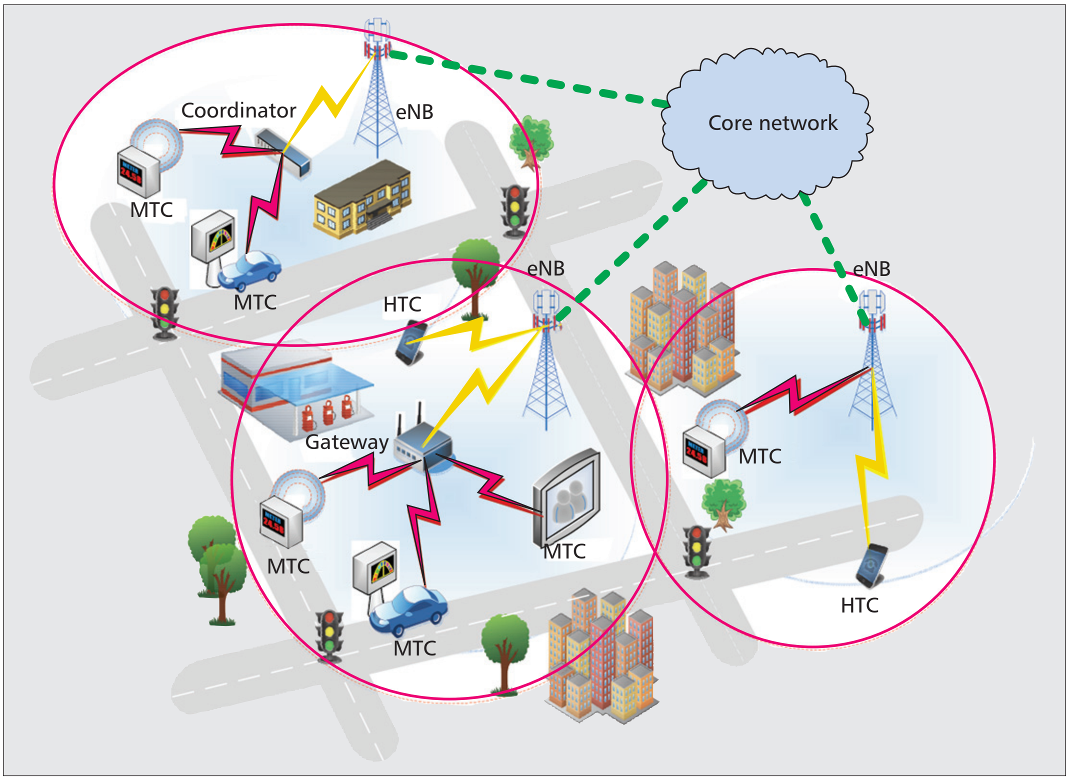

Figure 1. High-level illustration of cellular networks with MTC and HTC devices coexisting [6].

All HTCs and MTCs are provided services by the eNBs either directly or indirectly. From the view of network, the coexistence between HTCs and MTCs raises the problem of radio resource competition with each other in the same network.

Regardless of whether the entity requesting access to the cellular network is an MTC device, a dedicated M2M gateway, or a coordinator MTC device, it is necessary to establish a radio resource control (RRC) connection with the eNB in order to be able to transmit data. To do so, in LTE and LTE-A, a periodic amount of frequency-time resources are allocated for the physical random access channel (PRACH), through which RRC connections can be established [7]. Devices are informed of the available PRACH resources with the system information broadcasted by the eNB in either the broadcast or other downlink control channels. When a device attempts to connect to the eNB, the random access procedure comprises the exchange of the following four messages, which are also summarized in Fig. 2.

Message 1 — random-access preamble transmission: A device attempting to establish a connection transmits a randomly selected preamble (chosen from a set of a maximum of 64 possible preambles, even though some of them may be reserved for prioritized access) in the next available RACH resource. The eNB can estimate the transmission time of the device by detecting its random-access preamble. Since it is possible that multiple devices will send preambles simultaneously, there may be collisions during the access procedure. These collisions are detected in message 3, as explained later.

Message 2 — random-access response (RAR): For each detected preamble in each access resource (slot), the eNB sends a time advance command to all the devices that have transmitted a specific preamble in a specific PRACH to adjust synchronization. In addition, the eNB allocates transmission resources to the devices that sent a given preamble in a given PRACH for the transmission of message 3. If a device sends message 1 and does not receive the RAR from the eNB in a certain period of time, called RA-response window size, or receives a RAR that does not attach information related to its access request, it postpones the access attempt to the next RACH opportunity. This can happen due to either a collision or channel fading that has corrupted the transmitted RAR. The postponement periods are determined by the backoff parameters indicated. For example, upon a failure in the first attempt, the value of the backoff index is 1, and the slot duration lasts 10 ms. Therefore, the device will attempt new access in a random time between 0 and 10 ms.

Message 3 — RRC connection request: The device that sent message 1 to initiate the access procedure and receives the RAR associated to its transmitted preamble transmits, in the assigned resources notified in the RAR, its temporary terminal identity to the eNB using the physical uplink shared channel (PUSCH) to request an RRC connection. If two or more devices have sent message 1 using the same preamble in the same PRACH, and the collision was not detected in message 2 (due to a constructive interference), message 3, will collide. To detect such collision, message 3 is transmitted with hybrid automatic repeat request (HARQ). Upon a maximum number of attempts to transmit message 3, a collision is declared, and access to the system is postponed.

Message 4 — RRC connection setup: The eNB sends information allocating resources to each of the devices that gained access, specifying their addresses. Therefore, the connection is established, and the device can start to transmit data.

Improving the RACH for MTC and HTC

As described in the previous section, the RACH for LTE and LTE-A is based on random-based contention access. Note that devices select a preamble according to the given rule and transmit in a slot, expecting to not collide with any other device. Indeed, the operation of RA is based on a variation of frame slotted ALOHA, which suffers from congestion when the number of contending devices is very high, as the probability of collision grows exponentially with the number of devices. Therefore, in the presence of a high number of MTC devices, especially with direct access, the access performance of HTC devices is degraded, thus jeopardizing human-based applications.

To deal with this limitation, many works on the RACH in LTE with M2M are being carried out. Some of the most relevant contributions are summarized in Table 1, and a comprehensive survey can be found in [9]. Most of these works focus on the optimization of existing networks for M2M traffic in isolated conditions (i.e., without taking HTC traffic into consideration). For example, the work in [10] provides an overview of the network architecture and features of MTC in the 3GPP network, and evaluates the performance of MTC using various access schemes in terms of average access delay, throughput, jitter, and energy efficiency. Other works focus on controlling intercell interference when the number of MTC devices is very high [2, 11–14] and the QoS requirements for different applications need to smoothly coexist [15].

In this article, we propose splitting the devices of a network into two groups (i.e., one with all the MTC devices and another one with all the HTC devices). Then we study two backward-compatible ways of providing each of these groups with access priority against the other group:

- Priority HTC (PHTC): HTC is always prioritized against MTC in the case of collision.

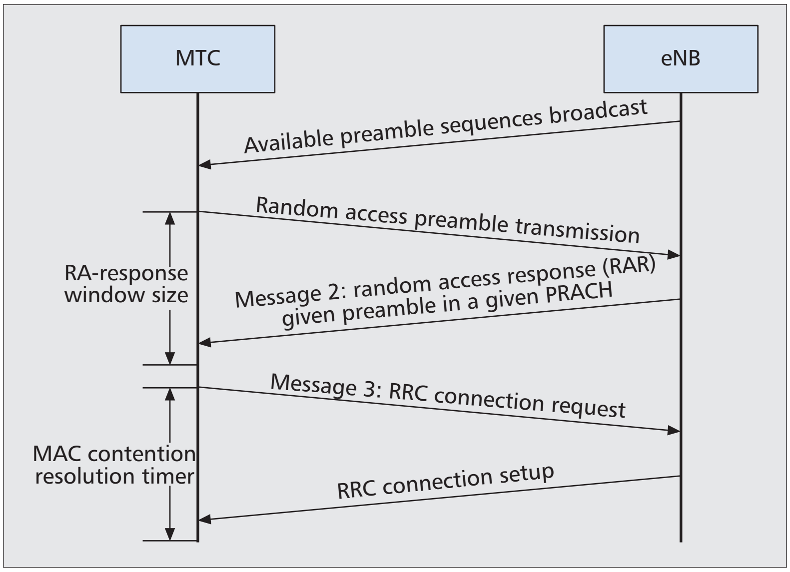

Figure 2. Random access procedure in LTE/LTE-A networks [8].

- Priority MTC (PMTC): MTC is always prioritized against HTC in the case of collision.

The eNB can distinguish between HTCs and MTCs through their terminal identities contained in message 3 of the random access procedure or by applying a barrier mechanism (i.e., using a different set of predefined preambles for each group). Priority is granted in message 4, when resources for transmission are granted. If there are multiple devices of one kind requesting access together, the one with the largest backoff time is granted access first. The backoff time of each device is recorded during the random access procedure and is used to determine the access priorities

These two priority classes embody two extremes: full priority to either human or M2M traffic. For practical rollouts, a weighted priority approach could be envisaged; however, according to the performance insights presented in the next section, this would not be needed.

Performance and Discussions

In this section, the performance of the two methods defined in the previous section is evaluated by means of computer-based simulations based on MATLAB software, where the operation of

Name	Evaluation quality	Intercell interference	HTC impact	Coordinator or gateway
ES-MACPA [3]	Energy consumption	No	No	Yes
K-means-based [4]	Energy consumption	No	No	Yes
RA preambles separation [6]	Throughput	No	Yes	No
Massive access management [7]	Jitter	No	No	No
Cooperative ACB [8]	Delay and throughput	Multicell and picocell	No	No
Multi-group random access [9]	Signal-to-interference ratio	Multicell	No	No

Table 1. Comparison of MTC access methods.

the RACH of LTE has been implemented. The focus is therefore on the RACH and not on actual data transmission.

The considered key performance indicators (KPIs) are:
- The blocking probability
- The average access delay
- The achievable duty cycle of devices when using the PHTC and PMTC techniques presented in the previous section

All these parameters are defined in the next subsection.

Definitions

The **blocking probability** is defined as the ratio of devices failing to access the eNB due to exceeding their maximum allowed access delay to the total number of devices attempting to get access.

The **average access delay** is defined as the average time elapsed from the moment when a device sends the first access request until the moment it succeeds and radio resources are allocated for transmission.

The **duty cycle** is defined as the ratio between the device active time (when the radio front-end is on) to the device sleeping time (when the radio front-end is off) and can be expressed as

$$\rho = \frac{(P_B T_{MAX}) + (1 - P_B) T_{access}}{T_{IN}}, \tag{1}$$

where P_B is the blocking probability, T_{MAX} is the maximum access delay in the case that the access is dismissed, T_{access} is the actual access delay in the case of successful access, and T_{IN} is the interarrival time (i.e., the time between two consecutive access requests).

Scenario

In order to evaluate the performance of the two techniques, PMTC and PHTC, in terms of the KPI defined above, we consider a single-cell cellular LTE network formed by 100 HTC devices and a number of MTC devices varying from 100 to 60,000.

In order to focus on the performance of the contention process of the RACH, ideal wireless channel conditions have been assumed. This means that an access request can only fail due to collisions with other devices and not due to channel fading. This suits this study, which focuses on a congested network. The values of the parameters used to simulate the RACH of LTE are listed in Table 2. Two typical scenarios are considered where different average access intervals are assumed: 20 minutes for *scenario 1* and 15 minutes for *scenario 2*.

Results

Figure 3a shows the blocking probability of HTC and MTC when using PHTC and PMTC as a function of the number of MTC devices in the network. For the PMTC methods, the blocking probability of HTC traffic seriously increases with the number of devices. It is worth observing that the difference between the two methods for MTC devices is very small. This means that MTC traffic is slightly impacted by the applied priority method. MTC devices are the ones caus-

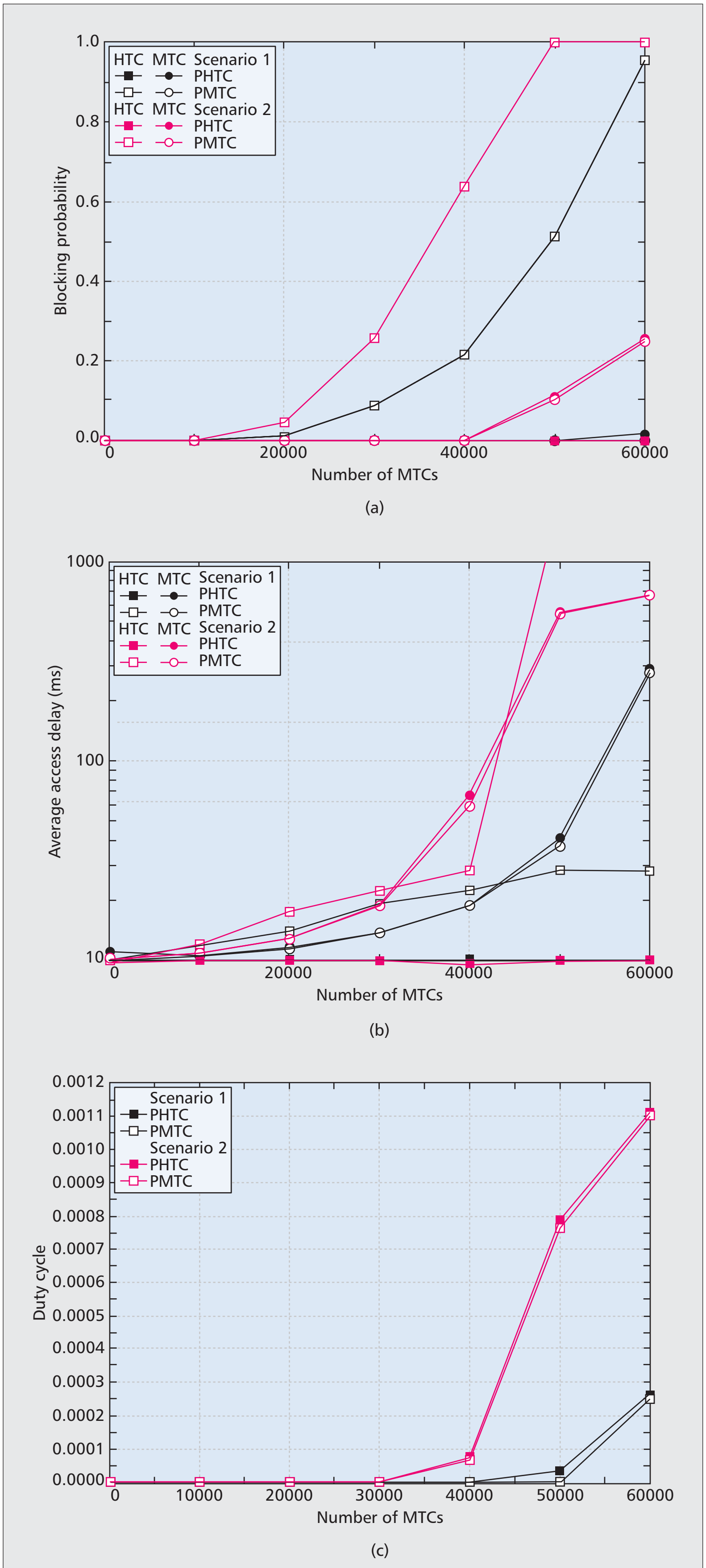

Figure 3. Performance of HTC and MTC Devices under two scenarios: a) blocking probability; b) average access delay; c) duty cycle of MTC devices.

ing the congestion of the network; thus, the treatment applied to HTC has little impact on the performance perceived by MTC devices.

Therefore, a network operator should always give highest priority to HTC in order to ensure good service for HTC while only marginally jeopardizing MTC. For delay-constrained M2M applications, a new group of MTCs (e.g., MTC-class II) could be defined with the same treatment as HTC devices so that their performance does not suffer from congestion when the number of devices is very high.

The average access delay of HTC and MTC devices is shown in Fig. 3b for both methods. In all cases, this value increases with the number of contending MTC devices. In addition, and as would be expected, with the PMTC method, the average access delay of HTC devices is higher than that with PHTC. This difference becomes less remarkable for the average access delay of MTC devices, in which case the two lines overlap, showing the same result in terms of average delay. Again, these results confirm that giving priority to HTC marginally impacts MTC, not the other way around. The value of the achievable duty cycle for MTC devices is shown in Fig. 3c. Results show that the duty cycle increases with the number of contending devices, and, as in the case of the blocking probability and average delay, this trend holds regardless of the priority method used.

The value of the duty cycle has a direct impact on the energy consumption of the devices and thus the lifetime of the network. Lower values of the duty cycle lead to lower power consumption and thus longer lifetimes. Let us assume, for example, that an MTC device consumes 1 W while on and transmitting over the cellular link, and close to 0 W when switched off. We further assume that the system accommodates 40,000 MTC devices, which, as per the above figures, allows access to the system in about 1000 ms and facilitates a duty cycle of about 0.007 percent. Then, using a small AA battery with about 3 W/h gives a lifetime of approximately 5 years; in comparison, if no duty cycling is used as in today's mobile phones, the lifetime would be only 10 h.

Moreover, in general, the performance of the network becomes worse for all KPIs when the average access interval of MTC is decreased to 15 minutes in *scenario 2* (compared to the 20-minute case considered in *scenario 1*). As would be expected, the closer the value of the average access interval for MTC devices to that of HTC devices, the less the difference that exists between giving priority to one group or the other.

Conclusions and Open Issues

The aim of this article was to expose the impact of massive MTC deployments on traditional cellular traffic. Corroborated by rigorous system level simulations, we clearly showed that under proper design, the impact of MTC onto HTC in the access mechanisms of LTE/LTE-A is negligible as long as HTC are given always priority to request access to the network. We have demonstrated that the duty cycle of MTC devices is indeed sufficiently low to facilitate years-long operation with small batteries. Our findings corroborate that LTE-A service providers will be able to support massive MTC systems without notable impact on current HTC traffic. However, several important design challenges remain, mainly pertaining to the improvement of MTC traffic itself.

Parameter	Value	
RA transmission time interval (TTI)	20 sf^{-1} = 20 ms	
{Back index} = {Backoff parameter}	{0, …, 12} = {0, 10, 20, …, 480, 960} ms	
	HTC	MTC
Number of devices	100	100 ~ 60,000
Interarrival rate (access requests/second) — Poisson distribution	1/300	1/900 and 1/1200
Maximum allowed access delay	100 ms	1000 ms

Table 2. Simulation parameters for the RACH of LTE [16].

Priority class definition and group management for MTC and HTC: The different requirements posed by HTC and MTC need to be mapped and quantified. It is necessary to define the requirements of newly emerged applications for MTC and create groups of applications with common requirements. This will allow for later particular optimization of the communication networks and a proper group management policy between HTC and MTC. So far, most research works deal with MTC and HTC as two big groups of applications; however, more granular definition of subtypes of requirements is needed.

Dynamic resource allocation between MTC and HTC: The resources in networks are shared by HTC and MTC devices dynamically. The resources can be initialized to HTC and MTC devices, respectively, according to the specified rule at the stage of network initialization. When the network detects or predicts in advanced that the network is overloaded by the excessive access attempts caused by the huge number of MTC devices, it dynamically allocates more RACH resources for MTC devices. One of the challenges in this case is when and how to make the adjustment decision. Also, it is still limited by the total amount of available resources.

Separated resources for MTCs in LTE-A: When the same resources are reused by the MTC and HTC devices, the congestion problem cannot be completely avoided. Therefore, separating the resources between HTC and MTC devices is a natural idea to decrease congestion and eliminate the effects of MTC over H2H communications. There are at least three ways to achieve such separation of resources: first, to split the radio resources in the same frequency band (e.g., RACH channels, access preambles, and radio resource blocks) to HTC and MTC devices separately; second, to allocate and out-

Our findings corroborate that LTE-A service providers will be able to support massive MTC systems without notable impact onto current HTC traffic. However, several important design challenges remain which mainly pertain to the improvement of MTC traffic itself.

of-band dedicated frequency band (e.g., below 1 MHz) to serve MTC devices using LTE technology; and third, to allocate an out-of-band dedicated frequency where an optimized technology, different from LTE, is used for MTC transmissions. The first two ways can take advantage of the existing infrastructure at the cost of decreasing the efficiency of LTE/LTE-A networks for HTC services. In contrast, the third option could optimally separate MTC and HTC, and provide MTC with an optimal technology tailored for MTC at the cost of having to deploy a completely new technology (infrastructure) that has to coexist with LTE/LTE-A.

Delay improvement: While current access delays are well within 100 ms, it does not suffice for a wide range of control applications. R13 of 3GPP ought to envisage design solutions facilitating a much quicker access on the order of a few milliseconds. This could likely be achieved by shortening the messaging sequence outlined in Fig. 2, where the biggest challenge will be to make the procedure backward-compliant.

Acknowledgment

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