The Impact of Massive Machine Type Communication Devices on the Access Probability of Human-to-Human Users in LTE Networks

Tiago P. C. de Andrade, Carlos A. Astudillo and Nelson L. S. da Fonseca
Institute of Computing - State University of Campinas, Brazil
{tiagoandrade, castudillo}@lrc.ic.unicamp.br, nfonseca@ic.unicamp.br

Abstract—**Machine-type Communication (MTC) enables devices to exchange information in an autonomous way without human intervention. Hence, new applications can be developed benefiting from a richer awareness of the surrounding environment. However, the deployment of MTC over cellular networks creates new challenges to the contention-based Random Access (RA) procedure as well as to resource allocation for MTC devices with low impact on Human-to-Human (H2H) services. In this paper, we analyze the impact of massive number of MTC devices on traditional H2H users in Long Term Evolution (LTE) network. We compare the performance of three Radio Access Network (RAN) overload control schemes proposed by the 3rd Generation Partnership Project (3GPP) for the contention-based RA procedure in this network. Results derived via simulation show that the access probability of Human-type Communication (HTC) users can be jeopardized by the large number of MTC devices. Therefore, enhanced mechanisms for the contention-based RA procedure in LTE network need to be investigated in order to support the expected large number of MTC devices and the traditional H2H users in the same infrastructure.**

Keywords*—*LTE networks, Random Access procedure, Machine-type Communication and RAN overload problem.

I. INTRODUCTION

Machine-type Communication (MTC), also known as Machine-to-Machine (M2M) communications, refers to machines or devices communicating without or with minimal human intervention. MTC enables several applications such as healthcare, Smart Grid, military applications and Intelligent Transport System. More recently, the introduction of the Internet of Things (IoT) concept has added new dimensions to the possibilities offered to these applications [1]. In the IoT, all types of real-word physical elements (sensors, actuators, personal electronic devices, or home appliances, amongst others) are able to autonomously interact with each other. In fact, it is envisioned that the IoT paradigm will lead to a world-wide network of tremendous amount of heterogeneously interconnected objects.

The Long Term Evolution (LTE) network has great potentials to support MTC, given its ubiquitous coverage and mobility support. While traditional Human-to-Human (H2H) users have requirements such as high data rate, mobility, and Quality of Service (QoS), MTC devices pose a different set of requirements, such as high device density, small packet size and low traffic volumes per device. In MTC, in general, there are thousands of devices with small amount of data and large number of signaling messages to be transmitted. Although the achievable data rate of LTE networks can be sufficient for M2M services, the design of the LTE network air interface cannot effectively support this type of communication, which causes a large signalling overload in the network and can affect the provisioning of QoS to H2H services. Such congestion problem can occur in the Radio Access Network (RAN) as well as in the mobile Core Network (CN).

In an LTE network, User Equipment (UE) devices perform contention-based Random Access (RA) procedure in order to access the network for the first time, recovering from radio link failure, uplink synchronization and sending Scheduling Request (SR) to solicit resource for transmission to the evolved NodeB (eNB). However, for this purpose, UE devices use a specific uplink channel, called Physical Random Access Channel (PRACH), which is a common transport channel that is used by UE devices to register to access the network after powering up [2]. PRACH is also used to perform location update after moving from one location to another as well as to initiate a call by setting up a connection from the UE device.

For instance, in a scenario with MTC devices such as smart meters, a heavy load is introduced to the PRACH because almost all UE devices can attempt to synchronize or to transmit data at the same time. Even if these smart meters are designed in a way that they do not transmit data synchronously when the power supply restores after a sudden power failure, a large number of devices may try to connect to the network at the same time. This situation can get worse if the failed devices try to access the network in consecutive attempts such that it can cause intolerable delays, packet loss or even service unavailability for both MTC devices and H2H users.

This is a main concern for the operation of LTE networks, motivated the search for potential improvements to facilitate M2M communications while using radio and network resources in an efficient way. In line with that, it has been proposed a set of solutions for potential RA mechanisms in future LTE deployments [3]. However, these solutions have not been evaluated yet.

The objective of this paper is to analyze how the large number of MTC devices can affect the performance of H2H users when MTC devices and H2H users share the Random Access Channel (RACH). In order to do this, we evaluate the performance of three RAN overload control schemes proposed by the 3rd Generation Partnership Project (3GPP) in a complex

978-1-4799-7162-6/14/$31.00 © 2014 IEEE

environment in which a large number of MTC devices coexist with typical H2H users in the cell coverage area.

The rest of this paper is organized as follows. Section II presents related work. Section III provides an overview on machine type communications. Section IV describes the RA procedure in LTE networks and Section V explains the RAN overload problem. Section VI shows simulation results for three RAN overload control schemes proposed by the 3GPP [3]. Finally, Section VII concludes the paper.

II. RELATED WORK

There are few papers in the literature that investigate the impact of massive MTC devices on the contention-based RA procedure of H2H users.

The work in [4] describes the impact of MTC devices on the RACH resources using an LTE network without any mechanism to avoid the RAN overload problem (i.e., it employs the traditional LTE RA scheme). It shows how the number of UE devices per RACH resource attempting contention-based RA procedure can affect the access probability and the access delay. This work considers a scenario with MTC devices only. Results do not distinguish between MTC devices and H2H users.

The authors in [5] present a comparison of three RA schemes, namely, traditional LTE RA scheme, Access Class Barring (ACB) scheme, and Extend Access Barring (EAB) scheme. They also consider only MTC devices in the performance evaluation.

Simulations to highlight the influence of MTC devices on H2H users were developed in [6], and packet loss ratio and access delay were assessed. However, it does not use any mechanism proposed by the 3GPP to prevent RAN overload. This work analyzes only the traditional LTE RA scheme.

In [7], the influence of M2M services on the scheduling of current LTE networks is presented. It uses the Bandwidth and QoS Aware (BQA) scheduler in this study. A shortcoming is that it does not consider the effect of the contention-based RA procedure in the performance evaluation. As shown in [4] and [5], the number of MTC devices can heavily affect the access probability to network resources and increase the access delay. The contention-based RA procedure can significantly affect the overall performance not only for the MTC devices but also for H2H users.

In summary, the above mentioned papers do not analyze the effect of MTC devices on the access probability of H2H users jointly with the schemes proposed by the 3GPP to overcome the RAN overload problem in LTE networks. Therefore, it is important to understand how the standardized RA schemes influence the performance of both type of UE devices. In addition, we need to know if it is necessary to improve the current contention-based RA schemes in order to support, in the same telecom infrastructure, a huge amount of MTC devices without affecting the service of traditional H2H users.

III. MACHINE TYPE COMMUNICATIONS

MTC is about enabling automated applications (or systems) that includes devices (machines or robots) communication over cellular networks [8]. MTC will facilitate the deployment of a variety of applications in a wide range of domains, such as transportation, health care, smart energy, supply and provisioning, city automation and manufacturing. MTC devices will be embedded in different environments (e.g., cars, cell towers and vending machines) and deployed in large quantities, connected to the Internet, forming the so-called IoT [7].

Depending on the communication between MTC devices and the eNB, M2M applications can be classified into two different categories: *(i)* data monitoring and *(ii)* data exchange. Data monitoring refers to one way data flow from MTC devices to eNB. The applications in this category include vital sign monitoring in health care system, monitoring of oil pipelines and on-demand charging transactions in e-commerce. In this category, MTC devices are used as sensors to report data for processing. Applications in the second category exchange data with a server using the eNB. MTC devices report data to server, and after raw data processing, the server provides feedback with processed data as well as instructions to be carried out using the eNB. Fleet management and smart meters in smart grids are two major applications in this category.

The use of LTE network air interface for M2M applications has several advantages. Network coverage of service providers make it possible to deploy MTC devices in most urban and rural areas, and the CN of the LTE network can provide seamless communication between MTC devices and M2M applications. The well established LTE network infrastructure makes it unnecessary to deploy new base stations dedicated to M2M communications, and service providers can better use the radio resources by sharing their under-utilized frequency bands between traditional H2H users and the new MTC devices.

However, as LTE networks are optimized for Human-type Communication (HTC) applications, there are several issues on MTC devices accessing cellular networks. Unlike H2H traffic, which is characterized by low frequency and high data rates, MTC usually have low data rates and has frequent transmissions. To achieve synchronization and ameliorate the contention, the overhead of MTC devices can be much larger than the size of actual application data. The problem is even worse for battery-powered MTC devices, which consume most of their power on data transmissions. Another important issue is overloading the RAN, which will be addressed in this paper.

IV. RANDOM ACCESS PROCEDURE

The RA procedure in LTE networks [9] can be classified into two operational modes, namely, contention-based RA and contetion-free RA procedures. The former is used by UE devices *(i)* to change the Radio Resource Control (RRC) state from *idle* to *connected*, *(ii)* to recover from radio link failure, *(iii)* to perform uplink synchronization, and *(iv)* to send SRs. The latter is used by UE devices to perform handover from one cell to another, or to recover from radio link failure. In this mode, the eNB has explicit control of when a UE device can initiate the RA procedure as well as which resources it will use. As the main challenges in MTC in LTE networks are in the contention-based operation, we focus on this mode, which comprises four steps, as shown in Figure 1.

In the first step, a UE device randomly selects one preamble sequence among M orthogonal preamble sequences and transmits the preamble sequence (msg1) in the next available PRACH. An LTE cell has 64 Zadoff-Chu orthogonal preamble sequences allocated for the RA procedure. These sequences have low Peak-to-Average Power Ratio (PAPR), which is an important property for energy efficiency. Some of these sequences are reserved for the contention-free RA procedure and the remaining ones are reserved for the contention-based RA procedure. The contention-based RA procedure sequences are further subdivided into two subgroups. The difference between the subgroups being the amount of uplink resources the device will transmit in the third step of the RA procedure. Since it is possible that multiple UE devices send preamble sequences simultaneously, collisions can occur during the contention-based RA procedure. A collision will occur if two or more UE devices randomly select the same preamble sequence.

In second step, when the eNB receives the preamble sequences (msg1) from UE devices, it detects which preamble sequences were transmitted, and obtains a Time Alignment (TA) value for the detected preamble sequences. Then, the eNB broadcast a Random Access Response (RAR) message (msg2) for each detected preamble sequence. This response includes a preamble sequence identifier, an uplink grant and TA information. UE devices use the preamble sequence identifier to identify the destination of the response. UE devices that transmitted a preamble sequence, are expecting to receive an msg2 message within a time window, which is configured by the eNB. If a UE device does not receive an RAR message within the configured time window, it increases the counter of preamble sequence transmission attempts and increases the PRACH transmission power. Then, the UE device repeats the first step unless the maximum number of access attempts has been reached. After the end of the RAR time window, the UE device has to wait at least 3 ms to transmit another preamble sequence.

In the third step, the UE device adjusts its uplink transmission time for synchronization according to the received TA information and transmits an L2/L3 message (msg3) on the allocated uplink resource. Once the msg3 message is transmitted, the UE device starts a contention resolution timer to check for possible collision. In the event of an RA collision, the collided preamble sequence can still be detected by eNB due to the low cross-correlation of the preamble sequences. In this case, the eNB is not aware of the collision and responds with an RAR message. Then, each of the colliding devices transmits its own msg3 message, which will again result in a collision at the eNB. If none of the msg3 messages are successfully decoded, the colliding devices will repeat the first step after the expiration of the contention resolution time window. If the eNB manages to decode one of the collided msg3 messages then it replies with the UE device identifier in the fourth step. Only the UE device that detects a match between the UE device identifier received in the fourth step and the identity transmitted in msg3 message can feedback a Hybrid Automatic Repeat Request (HARQ) positive acknowledgement to the eNB. The other colliding UE devices should discard the received message.

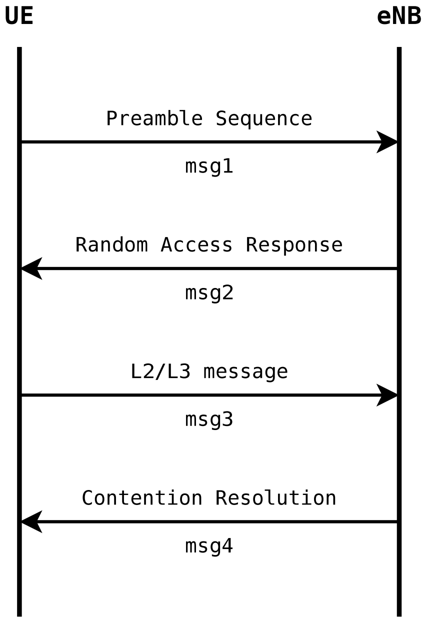

Figure 1. Contention-based Random Access procedure

In the last step, if the eNB successfully decodes the msg3 message, it transmits a Contention Resolution message (msg4) to the corresponding UE device. If before the contention resolution timer expires, a UE device successfully receives the msg4 message, then it successfully completes the RA procedure. Otherwise, it regards the previous RA attempt as a collision and needs to reattempt the RA procedure after performing a backoff mechanism until a successful RA procedure or the maximum number of preamble sequence retransmissions is achieved.

V. RADIO ACCESS NETWORK (RAN) OVERLOAD PROBLEM

Although the amount of data transmitted by MTC devices is small in most cases, the number of MTC devices in a cell is expected to be very large, and their data connection frequency is much higher than that of H2H users. A large number of MTC devices trying to access the network simultaneously leads to a low RA success rate and high network congestion in the RAN. This situation, also known as the RAN overload problem, results in shortages of RACH and control resources [10]. The former leads to extremely high RACH collision probability, and the latter means that insufficient control resources are available to send uplink grant and msg4 message to all UE devices before timer expiration. Both bring high probability of RA procedure failures and thus the overall network performance is severely degraded [3].

This problem should be prevented because it can cause unexpected delays, packet loss, and even service interruption [11]. In addition, every unsuccessful attempt wastes radio resources and battery energy, which is a precious resource of the MTC devices. The channel can be further overloaded when MTC devices perform several access attempts after collisions [1]. As a result, some devices may not achieve RA successfully even after several attempts.

The traditional LTE RA scheme, standardized by the 3GPP in the initial release of the Medium Access Control (MAC), does not consider the RAN overload problem. This scheme allows all UE devices to start their access attempts (i.e., the

RA procedure) immediately. Some schemes to overcome the RAN overload problem were introduced by the 3GPP in the release 11 of the LTE technology [3]. These schemes are: *(i)* the ACB, which deals with the excessive RAN overload problem by regulating the opportunity of UE devices to attempt the preamble sequence transmission; *(ii)* EAB, which, in case of congestion, restricts the access from UE devices configured for EAB while allows the access from other UE devices; *(iii)* the RACH Resource Separation (RRS), which splits RACH resources (i.e., the preamble sequences) into two separate pools, one for H2H users and another for MTC devices; *(iv)* Dynamic Allocation of RACH resources, in which the network may dynamically allocate additional RACH resources for MTC devices to use; *(v)* Slotted Access, in which slots are defined for MTC devices and each MTC device can only accesses the RAN at its dedicated access slot; *(vi)* Pull-based scheme, in which the MTC servers inform the MTC devices when they can transmit; and *(vii)* MTC Specific Backoff, in which the MTC devices can be instructed by the eNB to wait for a period of time different from that of the H2H users before trying again an RA attempt.

VI. PERFORMANCE EVALUATION

In this section, we evaluate and analyze the performance of different RAN overload control schemes proposed by the 3GPP for contention-based RA procedure in LTE networks. We selected two schemes among the above-mentioned RAN overload control schemes based on their relevance in the literature. We compare the performance of the ACB and RRS schemes, which were proposed for the RAN overload problem, as well as the traditional LTE RA scheme as a baseline.

Performance evaluation was conducted by using the LTE-Sim simulator version 5.0, which is an event-driven packet level simulator developed in C++ and widely used for simulating MAC functions of evolved UMTS Terrestrial Radio Access (E-UTRAN). We introduced the support to the contention-based RA procedure in the simulator and implemented the aforementioned mechanisms in order to analyze and compare their performance. The focus of this work is on the RACH overload problem and not on actual data transmission.

A. Simulation Setup

The simulation scenario is composed of a single cell, with one eNB and several UE devices (each UE device acts either as MTC device or H2H user). The number of H2H users was fixed to 50 and the number of MTC devices varied from 100 to 1500 in increments of 100. The UE devices were uniformly distributed around a radius of 0.5 Km. All simulations were replicated at least 33 times with different seeds.

All UE devices are assumed to be cell-synchronized and to have already received the configuration parameters related to the contention-based RA procedure in the beginning of the simulation.

A collision occurs when two or more UE devices select the same preamble sequence. All collided preamble sequences are considered failed (ignoring the power capture effect) after a pre-defined waiting time. Otherwise, the preamble sequence transmission is successful received with probability $1 - e^{-i}$, where i is the number of preamble sequence transmission [11]. Due to the power ramping technique, which is used to favor the delayed UE devices by increasing the transmission power after each unsuccessful access attempt, the access probability increases with the number of access attempts.

For the ACB scheme, all UE devices are assumed to belong to general ACs (0-9) and, therefore, the probability-based barring is applied to all UE devices in the simulation. The *ac_BarringFactor* and the *ac_BarringTime* parameter settings were 0.9 and 4 seconds, respectively.

Control signaling transmissions related to the system information are out of the scope of the simulations.

Table I summarizes the main configuration parameters used in the simulations.

B. Simulation Results

We analyze the influence of the number of MTC devices on the performance of H2H users for the aforementioned RAN overload control schemes. Our analysis is based on the following metrics, which were calculated for both UE device types: *(i)* access probability, which is the probability of successful completion of the RA procedure within the maximum number of preamble sequence transmissions; *(ii)* access delay, which is the delay between traffic arrival time at the MAC layer and the time when the corresponding RA procedure is successfully completed; and *(iii)* average preamble sequence transmissions, which is the sum of the total number of preamble sequences transmitted per UE device divided by the total number of UE devices in the network.

The figures presented in this section show the mean values with confidence intervals with 95 % confidence level derived using the independent replication method. All the above metrics are presented as a function of the number of MTC devices trying to access the network simultaneously.

Figures 2 and 3 illustrate the access probability of H2H users and MTC devices, respectively. The RRS scheme can provide high access probability to H2H users while simultaneously supporting MTC devices in the same infrastructure. However, the access probability of MTC devices sharply decreases as their quantity increases. This behaviour can be

TABLE I. SIMULATION PARAMETERS

Parameter	Value
System type	Single cell
System bandwidth	5 MHz
Cell radius	0.5 Km
PRACH configuration index	6
RA preamble sequence format	0
Available preambles	54
Number of UL grants per RAR	3
Number of CCEs allocated for PDCCH	16
Number of CCEs per PDCCH	4
Backoff indicator	2
HARQ retransmission probability	10%
Maximun number of preamble sequence transmissions	10
ra-ResponseWindowSize	5 ms
mac-ContentionResolutionTimer	48 ms
maxHARQ-Msg3Tx	5

explained because the RRS scheme reserves some RACH resources for H2H users which decreases the resources available to MTC devices. Thus, the probability of more MTC devices choosing the same RACH resource increases. When the ACB scheme is used, MTC devices achieve the highest access probability values among the evaluated schemes. Nevertheless, it does not guarantee good service for both MTC devices and H2H users because H2H users can access the network with a chance as low as 60 % when there is a large number of MTC devices in the cell. When the traditional LTE RA scheme is used, the access probability rapidly decreases as the number of MTC devices increases, reaching values close to 0 % for more than 700 MTC devices either to H2H users on to MTC devices. Therefore, the traditional LTE RA scheme (i.e., with no overload control) gets the worst-case scenario, where both MTC devices and H2H users have extremely low access probability for scenarios with more than 400 MTC devices.

The average number of preamble sequence transmissions of H2H users and MTC devices are shown in Figures 4 and 5, respectively. These results are directly related to those of the access probability and show a picture of how much preamble sequence transmissions are needed to complete the RA procedure when the number of MTC devices varies. Among the three schemes, RRS has the lowest number of preamble sequence transmissions for H2H users. On average, roughly four preamble sequence transmissions are needed to achieve the values of access probability showed in Figure 2. Thus, a network that use this RAN overload control scheme allows MTC devices to access the network with fewer transmissions. We can also observe that the higher the number of preamble sequence transmissions, the lower is the access probability. This means that as the number of MTC devices increases, H2H users need more access attempts to access the RACH because more collisions are happening in the network as a consequence of the large number of MTC devices in the cell. When the access probability values are close to zero (Figures 2 and 3) the average number of preamble sequence transmissions is near to ten, which is the maximum number of preamble sequence transmissions allowed in the simulations. In these situations, almost all H2H users cannot access the services provided by the network.

The average access delay values are shown in Figures 6 and 7, for H2H users and MTC devices, respectively. In these figures, the ACB scheme exhibits the highest values among the evaluated schemes (delay values of one second or more). This is because the ACB scheme uses a range of high values for its waiting time parameter (some seconds), jeopardizing the access delay to applications that have a small delay requirement such as some H2H applications. Therefore, this scheme is not a good option for applications that are delay-

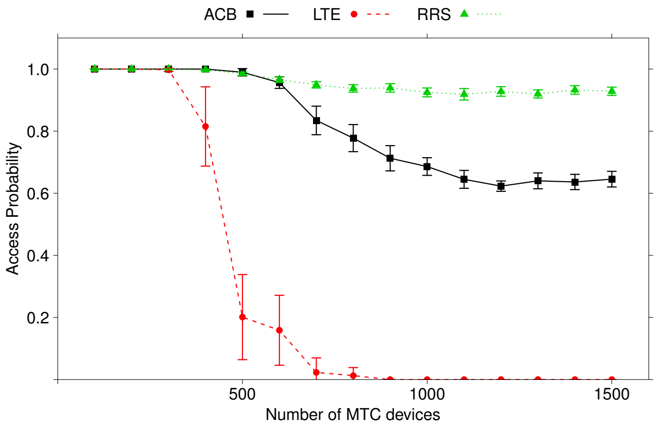

Figure 2. Access probability for H2H users

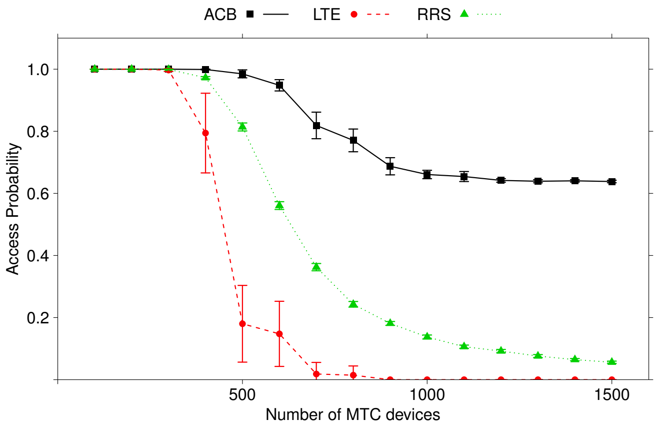

Figure 3. Access probability for MTC devices

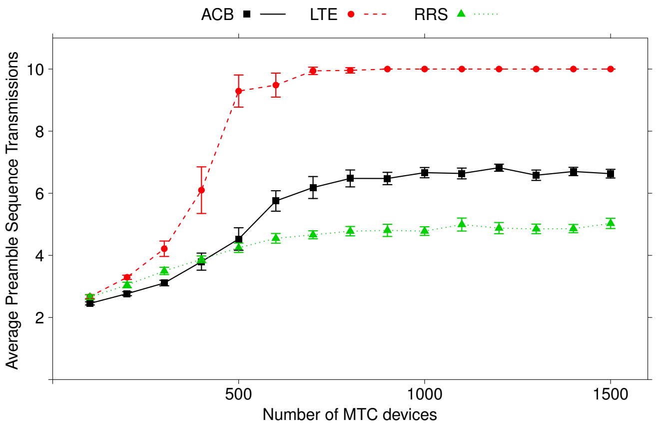

Figure 4. Average preamble sequence transmissions for H2H users

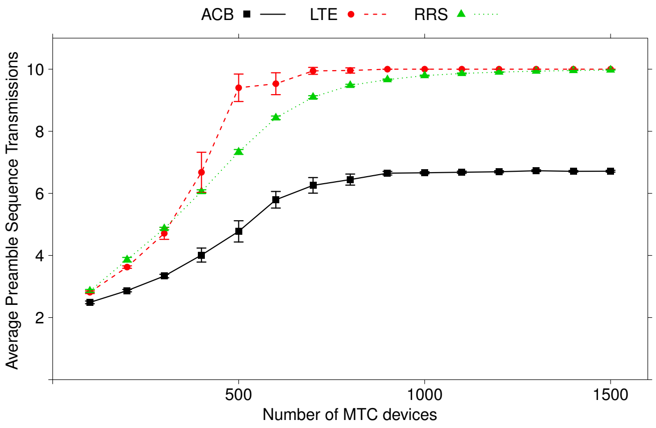

Figure 5. Average preamble sequence transmissions for MTC devices

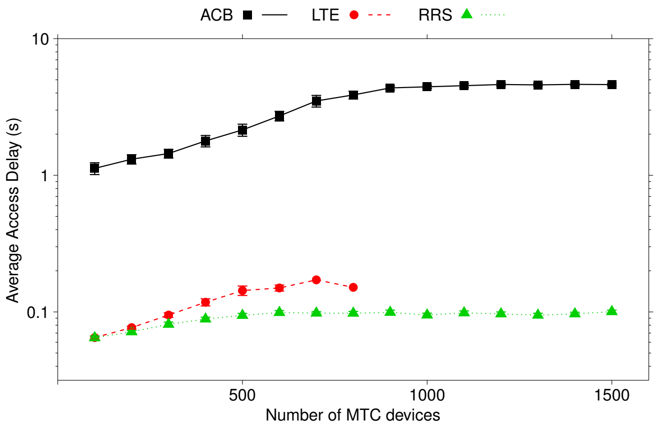

Figure 6. Average delay for H2H users

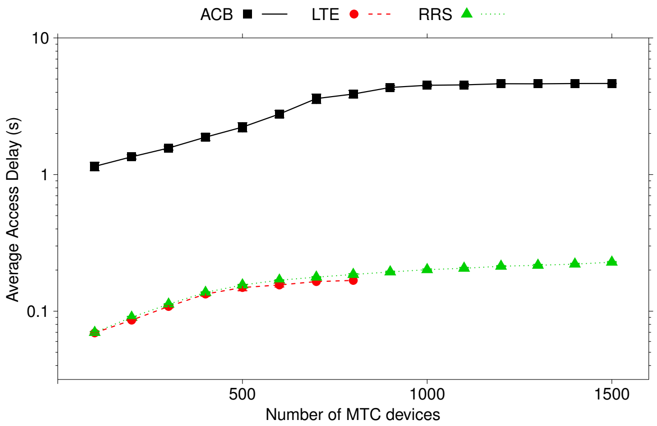

Figure 7. Average delay for MTC devices

constrained. On the other hand, the traditional LTE RA scheme does not have any benefit even having a short delay since the access probability rapidly decreases as shown in Figures 2 and 3. The RRS scheme has the lowest delay values either to H2H users as MTC devices.

VII. CONCLUSION

The aim of this work was to evaluate the effect of a massive number of MTC devices on traditional LTE network traffic. We highlighted the impact of massive MTC devices on the PRACH of traditional H2H users. Two standardized RAN overload control schemes and the traditional LTE RA scheme were evaluated and their results compared. For all evaluated schemes, we found that the number of MTC devices can highly affect the access probability of H2H users. We also observe that the access probability values of MTC devices are much lower than those of H2H users. Thus, it is necessary to propose enhanced RAN overload control schemes that support co-existing H2H users and MTC devices in the same cellular network infrastructure. Moreover, the telecom network architecture needs to be improved to accommodate the new M2M service requirements without sacrificing the quality of H2H services.

ACKNOWLEDGMENT

This work was supported by the research agencies Coordination for the Improvement of Higher Education Personnel (CAPES) and National Council for Scientific and Technological Development (CNPq).

REFERENCES

[1] T. Taleb and A. Kunz, "Machine type communications in 3GPP networks: Potential, challenges and solutions," *Communications Magazine, IEEE*, vol. 50, no. 3, pp. 178–184, March 2012.

[2] 3GPP, "Evolved Universal Terrestrial Radio Access (E-UTRA); Physical channels and modulation," 3rd Generation Partnership Project (3GPP), TS 36.211, October 2013. [Online]. Available: http://www.3gpp.org/ftp/Specs/html-info/36211.htm

[3] ——, "Technical Specification Group Radio Access Network; Study on RAN Improvements for Machine-type Communications," 3rd Generation Partnership Project (3GPP), TR 37.868, September 2011. [Online]. Available: http://www.3gpp.org/ftp/Specs/html-info/37868.htm

[4] A. Lo, L. Y. Wei, M. Jacobsson, and M. Kucharzak, "Enhanced LTE-Advanced random-access mechanism for massive machine-to-machine (M2M) communications," in *27th Wireless World Research Forum (WWRF27)*, 2011.

[5] U. Phuyal, A. Koc, M.-H. Fong, and R. Vannithamby, "Controlling access overload and signaling congestion in M2M networks," in *Signals, Systems and Computers (ASILOMAR), 2012 Conference Record of the Forty Sixth Asilomar Conference on*, November 2012, pp. 591–595.

[6] N. Kouzayha, N. C. Taher, and Y. Ghamri-Doudane, "Towards a better support of machine type communication in LTE-networks: Analysis of random access mechanisms," in *Advances in Biomedical Engineering (ICABME), 2013 2nd International Conference on*, September 2013, pp. 57–60.

[7] T. Potsch, S. Khan Marwat, Y. Zaki, and C. Gorg, "Influence of future M2M communication on the LTE system," in *Wireless and Mobile Networking Conference (WMNC), 2013 6th Joint IFIP*, April 2013, pp. 1–4.

[8] R. Hu, Y. Qian, H.-H. Chen, and A. Jamalipour, "Recent progress in machine-to-machine communications," *Communications Magazine, IEEE*, vol. 49, no. 4, pp. 24–26, April 2011.

[9] 3GPP, "Evolved Universal Terrestrial Radio Access (E-UTRA); Medium Access Control (MAC) protocol specification," 3rd Generation Partnership Project (3GPP), TS 36.321, July 2013. [Online]. Available: http://www.3gpp.org/ftp/Specs/html-info/36321.htm

[10] 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.

[11] M. Gerasimenko, V. Petrov, O. Galinina, S. Andreev, and Y. Koucheryavy, "Energy and delay analysis of LTE-advanced RACH performance under MTC overload," in *Globecom Workshops (GC Wkshps), 2012 IEEE*, December 2012, pp. 1632–1637.