Random Access Mechanism for RAN Overload Control in LTE/LTE-A 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*—The Long Term Evolution (LTE) and LTE-Advanced technologies aim at providing improved users' experience by increasing data rate, enhancing coverage and supporting Quality of Service (QoS) to different service classes. However, a large number of User Equipment (UE) devices trying to access the network in a short period can overload the Radio Access Network (RAN). In this situation, more access attempts to the system are made than it can handle, resulting in low access probabilities and poor network performance. In this paper, we introduce the QoS-Aware Self-Adaptive RAN Overload Control (QoS-Dracon) mechanism to reduce the RAN overload problem, taking into account users' QoS requirements. This is achieved by employing a QoS Class Identifier-dependent backoff scheme and an Access Class Barring-based RAN overload control mechanism. QoS-Dracon prioritizes delay-sensitive UE devices over delay-tolerant ones when performing Random Access (RA) procedure. Results derived via simulation show that the proposed mechanism yields satisfactory access delays for delay-sensitive users regardless of the UE devices type attempting to access the channel.**

***Keywords*—LTE-A networks, random access procedure, Machine-to-Machine communications and RAN overload.**

I. INTRODUCTION

The massive number of Machine Type Communication (MTC) devices expected to share Long Term Evolution (LTE) networks with traditional Human Type Communication (HTC) users can overload the Radio Access Network (RAN). Although the achievable data capacity of LTE/LTE-Advanced (LTE-A) networks can be sufficient for Machine-to-Machine (M2M) communication, the air interface cannot effectively support this new type of communication. MTC refers to communication between machines or devices either with minimal or no human intervention. Even though the transmission rate of MTC devices is small, in most cases, the frequency they access the network is much higher than that of HTC users as a consequence of the typical large number of MTC devices. A large number of devices trying to access the network simultaneously leads to high RAN overload and low access probability. Specifically, this situation results in shortages of two radio resources: Physical Random Access Channel (PRACH) and control channels [1]. The former leads to extremely high Random Access Channel (RACH) collision probability, and the latter implies on insufficient control resources to schedule uplink transmissions during the contention-based Random Access (RA) procedure. Both degrade the access to PRACH and, consequently, the overall network performance can be severely jeopardized [2]. This problem should be prevented since it causes unexpected delays, packet losses, and even service interruption [3]. In addition, every unsuccessful attempt wastes radio resources and battery energy. Moreover, the network can be further overloaded when User Equipment (UE) devices try to access the network repeatedly after an event of collision [4]. As a result, some UE devices may not successfully access the channel even after several attempts.

MTC devices can support a broad range of applications, each with its own specific Quality of Service (QoS) requirements. While some M2M applications such as smart metering [5] are not delay-sensitive, others such as eHealth [6] are delay-sensitive and have strict Packet Delay Budgets (PDBs). In addition, the cellular network must guarantee that the support to M2M services does not affect the support to Human-to-Human (H2H) services.

Currently, Access Class Barring (ACB)-based mechanisms are the best way to deal with the RAN overload problem in LTE networks [2]. ACB is based on the idea that certain access classes, which are indicated by means of network broadcasting information, are not allowed to access the network in some PRACH opportunities. ACB-based mechanisms that take into account QoS requirements [7] [8] consider all HTC users as belonging to a single access class and MTC devices into different access classes. Moreover, these MTC access classes are generally based on new QoS Class Identifiers (QCIs), which are not standardized, affecting the network interoperability. Another available solution is the class-dependent backoff mechanism, which cannot ameliorate a heavy RAN overload by itself, but can decrease RAN overload when used in conjunction with an ACB-based scheme [7] [8].

In line with that, this paper proposes the QoS-Aware Self-Adaptive RAN Overload Control (QoS-Dracon) mechanism in which reactions to sudden changes in RAN load are performed timely and consider the QoS requirements of UE devices. The main idea of the QoS-Dracon mechanism is to block the preamble sequence transmissions of delay-tolerant UE devices when the RAN is overloaded. Additionally, our proposal complements this blocking-based mechanism by employing a QCI-dependent exponential backoff scheme that helps to spread access attempts in time. Unlike other proposals in which high priority is given to all HTC users regardless of their QoS requirements, at the expense of degrading the QoS support to MTC devices [8], the QoS-Dracon mechanism prioritizes UE devices based on their delay requirements as specified by their QCIs and not on the terminal type.

The core of QoS-Dracon mechanism is an Access Class Barring (ACB) scheme that collects information about the RAN load condition, makes decision based on the collected information and blocks accesses of delay-tolerant UE devices in order to decrease the RAN overload when necessary. To estimate the RAN load, we propose a simple method based on the number of preamble sequence transmissions needed to effectively access the network. An important feature of the QoS-Dracon mechanism is that it is based on the QCIs standardized by the 3rd Generation Partnership Project (3GPP), guaranteeing interoperability between different service providers and network domains. Results derived via simulation show that the proposed mechanism can support access differentiation based on the QCI value as well as maintain low access delays for delay-sensitive UE devices.

The rest of the paper is organized as follows. Section III briefly describes the contention-based RA procedure. Section IV introduces the RA overload control mechanism proposed for the RAN overload problem. Section V shows the performance evaluation of the mechanism derived via simulation. Section II presents related work. Finally, the Section VI concludes the paper.

II. RELATED WORK

There are few papers in the literature that investigate RA mechanisms involving RAN overload control jointly with QoS-aware solutions in LTE/LTE-A networks.

De Andrade et al. [9] show a comparison of three RA mechanism proposed by the 3GPP in [2], namely, LTE, ACB and RACH Resource Separation (RRS). The simulation environment used in [9] is the same used here. However, the work in [9] does not take into account that M2M and H2H terminals can have different priorities. The authors show that the access delay of both MTC devices and HTC users can be greatly jeopardized if the QCIs are not taken into account at the moment of performing the RA procedure.

The work in [10] considers that M2M can lead to an unexpected high collision rate when it is used together with the traditional mobile communication service under the same telecom infrastructure with a large number of MTC devices. In order to solve this problem, the authors proposed a Self-Adaptive Persistent Contention (SPC) mechanism to schedule MTC devices in a periodical manner. Moreover, the proposed scheme also achieves significant improvement of uplink bandwidth utilization while maintaining backward compatibility with existing wireless communication frameworks.

The authors in [11] considered the dynamics of the signalling load on the PRACH to develop the Self-Optimizing Overload Control (SOOC) mechanism, which can respond to sudden changes on the PRACH load condition in a timely manner. The core of SOOC is a control loop that performs congestion monitoring, decision-making and adjustment of PRACH resources. SOOC includes a composite overload mechanism that comprises dynamic PRACH resource allocation, PRACH resource separation, the Access Class Barring scheme, the slotted-access scheme and the p-persistent scheme. However, this work treats differently M2M and H2H access attempts by prioritizing all HTC users over MTC devices. Moreover, it does not take into account the QoS requirements of different applications and as a consequence this mechanism can greatly jeopardize the performance of delay-sensitive applications.

In [8], the Prioritized Random Access (PRA) mechanism is proposed to solve the RAN overload problem while supporting QoS provisioning to different classes of MTC devices. This is achieved by pre-allocating PRACH resources for different M2M classes with class-dependent backoff procedures and preventing a large number of simultaneous PRACH attempts by using Dynamic Access Barring (DAB). However, this paper considers all HTC users as belonging to the same access class.

The work in [7] introduced an integrated class-dependent backoff/ACB scheme to address the RAN overload issue. It uses system load information and classification information of MTC devices to generate MTC specific backoff intervals. The ACB scheme is used as a preliminary stage of numbering control while the class-dependent backoff scheme is used as a secondary stage to spread the accesses of many MTC devices in time. However, this work separates the UE devices into two access classes: one for HTC users and high-priority MTC devices and the other for low-priority MTC devices. As the previously mentioned papers, it considers all HTC users as having the same access priority.

In summary, the mentioned papers do not consider the use of the QCIs defined by the 3GPP to make decision about how to perform the RA procedure. For all of them, HTC users have the same access priority, independently of their QoS requirements. This can lead to degradation of QoS provisioning for MTC devices with strict QoS requirements.

III. RANDOM ACCESS PROCEDURE

The RA procedure in LTE networks [12] can operate into two modes: contention-based and contention-free. 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 Scheduling Requests (SRs). The latter is used to perform handover. In this mode, the evolved NodeB (eNodeB) has explicit control of when a UE device can initiate RA as well as which resources it will use. We focus on the contention-based operation since the main challenges in access are related to this operation mode.

The contention-based operation comprises four steps. In the first step, the UE devices randomly select one preamble sequence among $64 - N_c$ orthogonal ones, where N_c is the number of preamble sequences reserved for the contention-free RA procedure, and transmit it in the next available PRACH (msg1). Since it is possible that multiple UE devices send the same preamble sequence simultaneously, collisions can occur during the contention-based RA procedure.

In the second step, when the eNodeB receives the msg1 message from the UE devices, it detects which preamble sequences were transmitted. Then the eNodeB broadcasts a Random Access Response (RAR) message (msg2) to each detected preamble sequence. UE devices use the preamble sequence identifier to determine the destination of the response. UE devices, that transmitted a preamble sequence, expect to receive an msg2 message in a time window configured by the eNodeB. If a UE device does not receive an RA response within the configured time window, it increases the counter of preamble transmission attempts and increases the transmission power. Then, the UE device repeats the first step unless the maximum number of access attempts has been reached.

In the third step, the UE device adjusts its uplink transmission time for synchronization according to the received Time Alignment (TA) information and transmits an L2/L3 message (msg3) on the allocated uplink resource. Once the message is transmitted, the UE device starts a contention resolution timer to check if collision occurred.

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

IV. QoS-AWARE SELF-ADAPTIVE RAN OVERLOAD CONTROL MECHANISM

As previously mentioned, an RA scheme integrating ACB and class-dependent backoff mechanisms is one of the most efficient approaches to tackle the RAN overload problem. Thus, we use these techniques together to develop the QoS-Dracon mechanism. QoS-Dracon takes into account the QoS requirements of each UE devices by allowing UE devices with strict QoS delay requirements to perform RA and by blocking access of other UE devices in RAN overload situations.

The proposed mechanism differentiates the access of several UE devices based on QCI values in the LTE standard. The UE devices are divided into two groups according to their QoS requirements: the delay-sensitive and the delay-tolerant groups, as showed in Table I. The former contains UE devices belonging to QCIs that cannot support large access delays, while the latter contains UE devices belonging to QCIs that can support large access delay.

QoS-Dracon implements an Access Class Barring (ACB)-based scheme in the eNodeB that collects information about the RAN load condition, makes decisions based on the collected information and blocks the accesses of delay-tolerant UE devices when necessary. Additionally, a QCI-Dependent Exponential Backoff scheme is used in every UE device to spread access attempts in time when the network is congested.

TABLE I. QoS-DRACON CONFIGURATION

QCI	PDB (ms)	Access Class	λ	Example Services
1	100	Sensitive	3	Conversational Voice
2	150	Sensitive	4	Conversational Video
3	50	Sensitive	2	Real Time Gaming
4	300	Tolerant	5	Video Streaming
5	100	Sensitive	3	IMS Signaling
6	300	Tolerant	5	TCP Based
7	100	Sensitive	3	Voice, Video and Interactive Gaming
8	300	Tolerant	6	TCP Based
9	300	Tolerant	6	TCP Based

A. *Access Class Barring (ACB) scheme*

The ACB scheme used in the QoS-Dracon mechanism comprises three phases, namely, Initialization, Monitoring and Adaptation. In the first phase, all variables involved in the monitoring phase are nullified in order to star a new monitoring period. The second phase is responsible for collecting information related to the RAN load condition during the monitoring period duration (T_m). To do so, if a UE device has delay-sensitive data, a RAN Overload Indicator (ROI) is included in the msg3 message in Step 3 of the RA procedure. The ROI conveys the number of preamble sequence transmission ($raRetryCounter$), which is a Medium Access Control (MAC) parameter that is incremented by 1 each time the UE device sends a preamble sequence. The ROI values range from 0 to the maximum number of preamble sequence transmission ($preambleTransMax$). A ROI value equals to $preambleTransMax$ means that the UE device has achieved the maximum number of preamble sequence transmissions. It also means that there is an increase in the RAN overload level.

In the third phase, the eNodeB reacts according to the ROI value by dynamically determining which UE devices can send the preamble sequence based on their QoS requirements. Depending on the RAN load level, the eNodeB decides which UE devices can send the preamble sequence in the next PRACH opportunities, giving priority to the UE devices with delay-sensitive data. To make the decision about which UE devices will be able to transmit their preamble sequences, the eNodeB needs to estimate the RAN load. To make such estimation, we propose a simple method based on the expression:

$$L_{RAN} = \frac{\sum_{i=1}^{n} ROI_i}{\sum_{i=1}^{n} (ROI_i + 1)} \tag{1}$$

where ROI_i is the ith ROI value received from delay-sensitive UE devices during a given monitoring period T_m. An L_{RAN} value close to 0 indicates that the RAN is not congested, whereas a L_{RAN} value close to 1 means that a high number of collision have occurred in the RAN. Depending on the L_{RAN} value, two different actions can be taken. If $L_{RAN} > \alpha$, the eNodeB blocks the preamble sequence transmissions of delay-tolerant UE devices. Otherwise, the eNodeB allows all UE devices to transmit their preamble sequences. The α parameter is a rational number between 0 and 1, and its impact on performance will be studied in next section. In order to inform the UE devices which access classes are allowed to transmit, the eNodeB broadcasts one bit as part of the system information. If the value of the bit is 1, the delay-tolerant UE devices are blocked, otherwise all UE devices can transmit their preamble sequences.

The monitoring period duration determines how often permission for preamble sequence transmission can be released to delay-tolerant UE devices. This means that a short monitoring period allows the network to quickly respond to RAN load changes while a long one implies that the network responds slowly. However, a short monitoring period incurs in high signaling overhead. The monitoring period can be configured from 1 ms to few hundreds ms as well as thousands ms depending on the operator's goals.

B. *QCI-Dependent Exponential Backoff scheme*

The core idea of this scheme is to delay the preamble sequence transmission of each UE device. Thus, before each preamble sequence transmission, the UE device postpones its transmission by a random number of PRACHs. This random value is in the range 0 to 2^{λ}, where λ is the backoff exponent, which depends on the standardized QCIs as shown in Table I. The delay requirement and the priority value were taken into account to define the value of this parameter. When the backoff period ends, the UE device checks if the preamble sequence can be transmitted by comparing its QCI value with the allowed group of QCIs.

V. PERFORMANCE EVALUATION

In this section, we evaluate and analyze the performance of the proposed RA mechanism for LTE/LTE-A networks. Performance evaluation was conducted by using the LTE-Sim simulator [13] version 5.0, which is an event-driven packet level simulator developed in C++ and widely used for simulating MAC functions of E-UTRA/E-UTRAN. We introduced the RA procedure in the simulator and implemented the proposed mechanism. The focus is on the RACH performance and not on actual data transmission.

A. *Simulation Setup*

The simulation scenarios comprise a single cell, with an eNodeB and several UE devices (each acts either as an MTC device or as an HTC user). The number of HTC users was fixed to 100 and the number of MTC devices varied from 200 to $3,000$ in increments of 200. Each UE device is assumed to have only one bearer with a single traffic class. The QCIs 1, 2, 5, 7 were used for delay-sensitive UE devices and QCIs 4, 8, 9 for delay-tolerant UE devices. The distribution of HTC users and MTC devices in each QCI is shown in Table II. The UE devices were uniformly distributed around a radius of 0.5 Km. All simulations were replicated 30 times with different seeds.

All UE devices are assumed to be cell-synchronized and to have already received the configuration parameters related to the RA procedure at the beginning of the simulation. This procedure is performed by the UE devices in order to request uplink resources to send the Buffer Status Report (BSR).

The simulation methodology [2] proposed by the 3GPP for performance evaluation of LTE networks with M2M support was used. A preamble sequence reception is successful with probability $1 - e^{-i}$ [2], where i is the number of preamble sequence transmissions. Due to the power ramping technique, which is used to favor delayed UE devices by increasing the transmission power after each unsuccessful preamble sequence transmission, the reception probability of preamble sequence increases with the number of preamble sequence transmissions. A collision occurs when two or more UE devices send the same preamble sequence. A UE device considers that a preamble sequence transmission has failed (ignoring the power capture effect) after pre-defined interval with no reception of the corresponding RAR message.

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

B. *Simulation Results*

The following metrics were assessed [9]: access probability, average access delay, and average preamble sequence transmissions. The figures presented in this section show mean values with confidence intervals of 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 RACH simultaneously for different QCIs in the 3GPP LTE standards.

Figures 1, 2 and 3 illustrate the access probability using the QoS-Dracon mechanism with α equal to 0.25, 0.5 and 0.75, respectively. When the value of α increases, the access probability decreases for scenarios with more than $2,000$ MTC devices in the cell. This behavior can be explained because the higher the value of α, the higher is the RAN load needed to detect that the RAN is overloaded for blocking the access of delay-tolerant UE devices. When the value of α is low, the eNodeB quickly detects the overload and blocks the access of delay-tolerant UE devices, decreasing the collision probability. Moreover, the number of low priority UE devices trying to access the network can be large which affects UE devices with low value of λ (i.e., delay-sensitive UE devices). The highest blocking probability for a scenario with 3000 MTC devices and α equals to 75 % is as low as 0.05.

The average access delay values for successfully completed RA procedures are shown in Figure 4, 5 and 6 for α equal to 0.25, 0.5 and 0.75, respectively. Access delays of delay-sensitive UE devices are clearly differentiated from those of the delay-tolerant UE devices. This shows that the QoS-Dracon mechanism can maintain low the access delays of delay-sensitive UE devices, sacrificing access opportunities of the

TABLE II. DISTRIBUTION OF THE UE DEVICES IN EACH QCI

QCI	H2H users	MTC devices
1	30%	-
2	20%	-
4	-	40%
5	10%	10%
7	-	10%
8	40%	-
9	-	40%

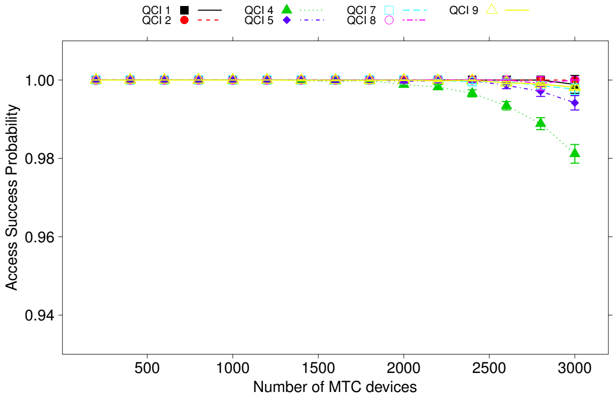

Figure 1. Access success probability for different QCIs with α equals to 25 %

TABLE III. SIMULATION PARAMETERS

Parameter	Value
System type	Single cell
System bandwidth	5 MHz
Cell radius	0.5 Km
PRACH configuration index	6
RA preamble format	0
Available preambles	52
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%
preambleTransMax	10
ra-ResponseWindowSize	5 ms
mac-ContentionResolutionTimer	48 ms
maxHARQ-Msg3Tx	5
T_m	50 ms
α	25%, 50% and 75%

delay-tolerant UE devices. Actually, the delay increases with the number of MTC devices, independently of the QCI value. All values of α yield a similar behavior for delay-sensitive QCIs when there is a low number of MTC devices in the cell. The minimum values of access delay were reached when the value of α was 0.25 and the maximum values were reached when the value of α was 0.75, for a large number of MTC devices.

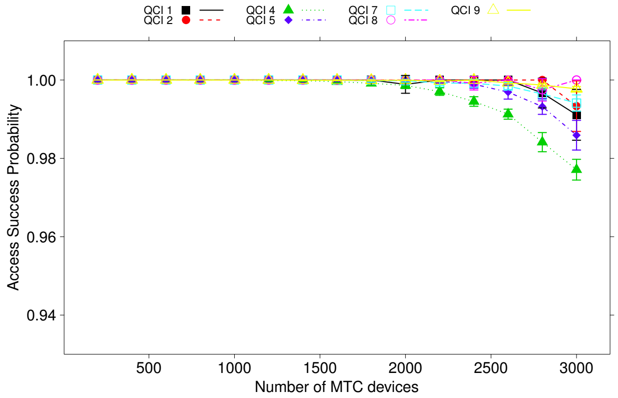

Figure 2. Access success probability for different QCIs with α equals to 50 %

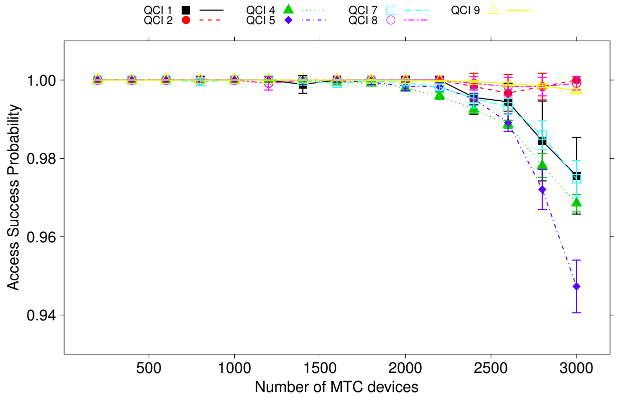

Figure 3. Access success probability for different QCIs with α equals to 75 %

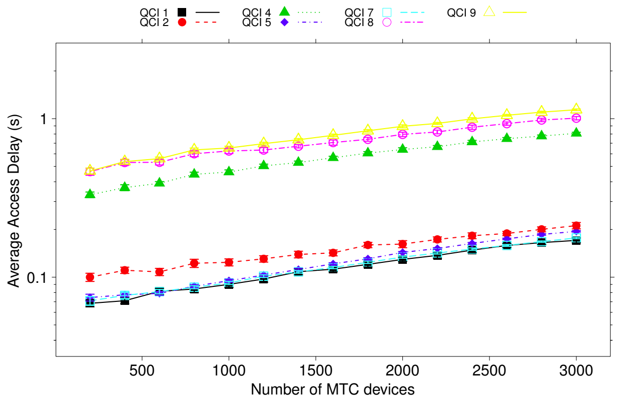

Figure 4. Average access delay for different QCIs with α equals to 25 %

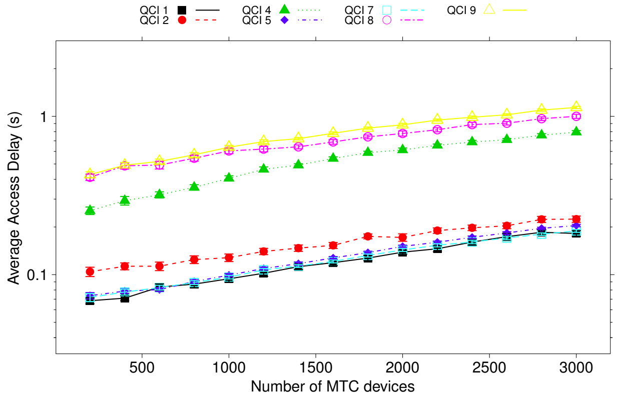

Figure 5. Average access delay for different QCIs with α equals to 50 %

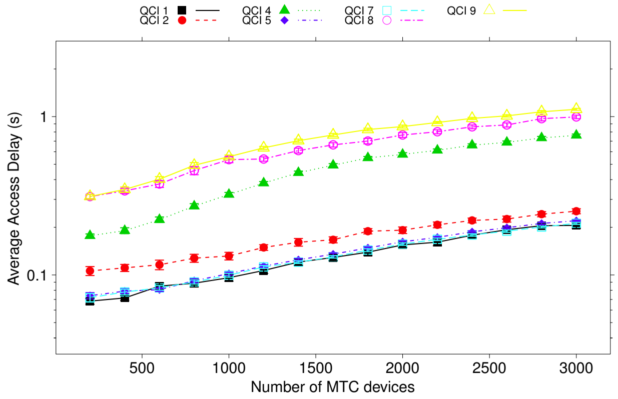

Figure 6. Average access delay for different QCIs with α equals to 75 %

The average number of preamble sequence transmissions needed to successfully complete the RA procedure is shown in Figure 7, 8 and 9 for values of α equal to 0.25, 0.5 and 0.75, respectively. The number of access attempts for all QCIs are very close, which indicates that it is not affected by the average access delay. This is a characteristic of mechanisms based on ACB/backoff schemes. Just as with the access probability, the value of α slightly impacts the average number of preamble sequence transmissions. The average number of preamble

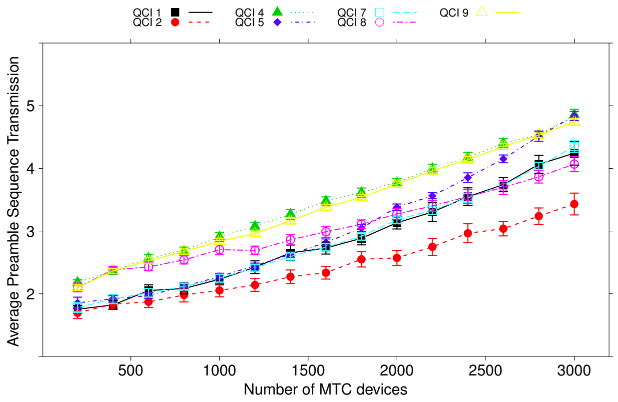

Figure 7. Average preamble sequence transmissions for different QCIs with α equals to 25 %

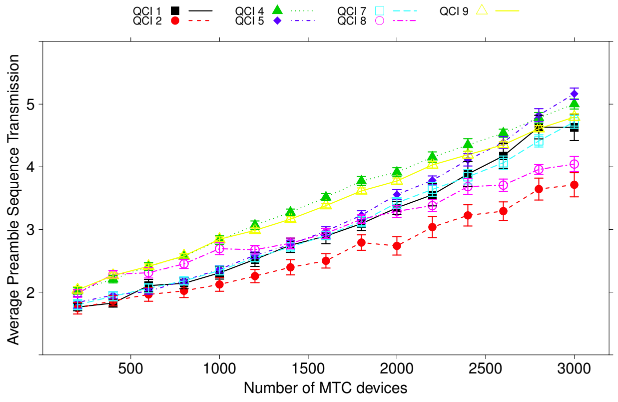

Figure 8. Average preamble sequence transmissions for different QCIs with α equals to 50 %

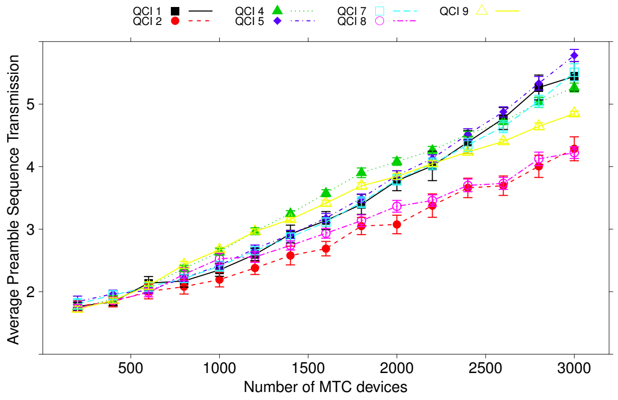

Figure 9. Average preamble sequence transmissions for different QCIs with α equals to 75 %

sequence transmissions produced when the value of α is 0.25 is lower than those produced when higher value of α are employed.

These results suggest that the value of α should be low for guaranteeing that delay-sensitive UE devices can receive the appropriate QoS provision with access probabilities close to 1 regardless of the QCI values.

VI. CONCLUSION

In this paper, we introduced QoS-Dracon, a mechanism for LTE/LTE-A networks that performs RA resource allocation by taking into consideration the RAN load as well as the MTC/HTC terminals QoS requirements. QoS-Dracon prioritizes delay-sensitive users over delay-tolerant ones when the RAN is overloaded. In order to determine the RAN load, a simple method based on the number of preamble sequence transmissions of delay-sensitive UE devices was proposed. Simulation results show that QoS-Dracon RA mechanism is able to decrease the RAN load while simultaneously taking into account different delay requirements of HTC users and MTC devices as originally standardized by the 3GPP.

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