Allocation of Control Resources with Preamble Priority Awareness for Human and Machine Type Communications in LTE-Advanced Networks

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***Abstract*—In this paper, we introduce the Preamble Priority-Aware (PPA) Packet Downlink Control Channel (PDCCH) resources allocation algorithm to provide Quality of Service (QoS) differentiation in the Random Access (RA) procedure of the LTE-Advanced technology. The PPA algorithm uses the preamble priority defined by the RA procedure and Radio Access Network (RAN) overload control schemes to make scheduling decisions. Results derived via simulation show that the proposed PDCCH algorithm significantly increases the chance of accessing the network as well as reducing random-access delays for user equipment employing prioritized preamble sequences. Thus, the proposed algorithm provides enhanced QoS support to prioritized users during intense RA attempts.**

***Keywords*—Handover, LTE-A networks, machine-to-machine communications, PDCCH scheduling algorithm, random-access procedure.**

I. Introduction

The Internet of Things (IoT) concept refers to a world of physical and virtual objects with sensing, computing and communications capabilities. Its realization heavily relies on technologies such as Machine-to-Machine (M2M) communications, also known as Machine-Type Communications (MTC) in the Third Generation Partnership Project (3GPP) terminology, which enables communication between machines that autonomously generates traffic with no human intervention [1]. The IoT requires that a massive number of geographically distributed devices be able to communicate in a reliable and efficient manner through the Internet. Given the ubiquity coverage, security and high capacity of the LTE-Advanced (LTE-A) cellular technology, it became a key enabling technology for the IoT connectivity landscape.

However, the MTC traffic can overload the traditional cellular networks because such networks were designed to attend Human Type Communication (HTC) traffic such as VoIP, video and web browsing. Unlike HTC traffic, the MTC traffic typically features large number of MTC devices transmitting sporadically small size packets. This MTC traffic patterns leads to shortages of different radio resources such as those of the Random Access Channel (RACH) and the various control channels [2]. These issues lead to high RACH collision probability and insufficient radio resources to schedule control and data messages. Thus, MTC devices can severely jeopardize the overall network performance for both traditional HTC users and MTC devices [3].

In the past few years, the 3GPP has proposed several improvements to the LTE-A standards, focusing mainly on the Radio Access Network (RAN) overload control problem and the reduction of User Equipment (UE) cost [4]. However, little attention has been given to the interaction of the Random Access (RA) procedure and Packet Downlink Control Channel (PDCCH) resource allocation and its impact on the performance of the network [5].

In LTE-A networks, a user or group of users can receive prioritized access during the initial phase of the RA procedure. For instance, in the contention-free RA procedure, the RAN explicitly informs the UEs the preamble sequence to be used in the RA procedure in order to avoid collisions. This preamble sequence is chosen from a poll of unique preamble sequences reserved for procedures requiring low latency such as handover. Another example is the RAN overload control scheme called RACH Resource Separation (RRS) which allows preamble sequences separation between HTC and MTC in order to alleviate the effect of the MTC on the HTC [6] [7]. By reserving an exclusive set of preamble sequences for a small number of UEs, the collision probability in the preamble transmission phase of the RA procedure is significantly reduced in the presence of massive access attempts [8].

Even though some priority can be given to a user through the above-mentioned methods, current PDCCH schedulers do not take into account the preamble priority to allocate control resources to sub-sequence RA-related messages derived from a prioritized preamble transmission. Thus, the effect of the PDCCH resource allocation on the access delay of user using high priority preamble sequences has been ignored in the literature [4]. Traditionally, the PDCCH scheduling mechanism prioritized RA-related messages over the other control messages (e.g., uplink grants, downlink assignments) [5]. However, control resources may not be enough to attend the huge demand in the presence of massive access attempts [4]. In this context, it is quite important to improve PDCCH resource allocation so that users utilizing high priority preamble sequences can be prioritized during control resource scheduling.

Most PDCCH scheduling algorithms in the literature (*e.g.,* [9] and [10]) do not explicitly consider RA-related messages into their scheduling decisions. To address this problem, three PDCCH resource allocation algorithm were recently proposed in [5]: the RA-Priorized (RAP), Lifetime-Aware (LTA) and GBR-Priorized LTA (GBR-LTA) algorithms. The RAP algorithm prioritizes RA-related messages over other control messages whereas the last two provide Quality of Service

(QoS) differentiation by taking into account both the specific waiting timer of the various control messages involved in the RA procedure and the QoS requirements of the downlink and uplink traffic. However, these algorithms and others in the literature [9] [10] do not differentiate among user utilizing high priority preambles and low priority preambles when creating the priority queue of subsequent control messages. Kim *et. al* proposed the Prioritized Random Access (PRA) scheme, which enables UEs to indicate the priority of their preamble transmissions by means of their transmiting power level [11]. However, the performance of this scheme can be highly affected by radio impairments such as fading, interference, etc.

This paper proposes a preamble priority-aware PDCCH scheduling algorithm so that the priority of different preamble sequence groups, as defined by the RA scheme and RAN overload control schemes for the initial phase of the RA procedure, can be maintained for the subsequent RA-related messages sent by the evolved NodeB (eNB) to the UEs. It considers preamble sequences for both contention-free and contention-based and the preamble priority defined for the initial phase of the RA procedure for the allocation of control resources.

The rest of the paper is organized as follows. Section II briefly introduces the RA procedure and the PDCCH structure of the LTE-A technology. Section III introduces the proposed preamble priority-aware PDCCH scheduling algorithm. Section IV assesses the performance of the proposed algorithm via extensive simulations and discusses the simulation results. Finally, the Section V concludes the paper.

II. LTE Background

This section introduces some concepts in the Long Term Evolution (LTE) technology, particularly those related to the RA procedure, the PDCCH as well as their interaction.

A. Packet Downlink Control Channel

Among the various downlink control channels defined to support the functionality of an LTE network, the PDCCH[1] performs a critical task to both RACH and data channels. It conveys Downlink Control Information (DCI) messages such as Random Access Response (RAR), Contention Resolution (CR), uplink grants, downlink assignments and power control commands. The RAR and CR messages are the two control messages directly related to the RA procedure. The last three control messages are used to allocate radio resources to downlink and uplink data channels.

The DCI messages use a certain number of Control Channel Elements (CCEs), which are the minimum radio resource unit in the PDCCH. The amount of CCEs used by each DCI message is known as CCE aggregation level and mainly depends on its format (one for each propose) and the UE channel quality. These messages are allocated in the mainstream of the PDCCH but the UE does not have *a priori* information about the exact location of the messages addressed to it. Each UE looks for DCI messages in two region within the PDCCH: the common search space (CSS) and the dedicated search space (DSS).

In the Release 8 of the 3GPP standard, the control channel occupies up to the first 3 symbols of each Physical Resource Block (PRB) in a Frequency Division Duplexing subframe. In release 11, a new channel called enhanced PDCCH (ePDCCH) was proposed to alleviate the shortage of control resources. This new control channel uses some Physical Downlink Shared Channel (PDSCH) resources to send control messages. However, an RAR message, which is located in the common search space, cannot be sent through this channel because it only supports dedicated search space. For MTC devices Cat M1, another channel, known as MTC PDCCH (MPDCCH), was defined to support both CSS and DSS on resources traditionally dedicated to the PDSCH.

B. Random-access procedure

The RA procedure in LTE-A networks can be executed in two operational modes: contention-free (Fig. 1(a)) and contention-based (Fig. 1(b)). The former is used to perform handover and to re-establish synchronization prior to downlink data transmission. On the other hand, the latter is commonly used in the following cases: (*i*) initial access to the network, i.e., when the radio interface is turned on; (*ii*) to request uplink resources upon arrival of uplink data at the UE buffer if data and control resources are not assigned to the UE; (*iii*) to re-establish a connection after a radio failure; and (*iv*) loss of uplink synchronization.

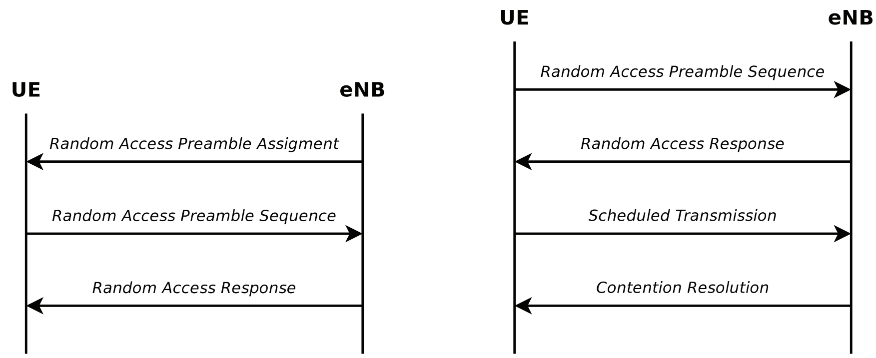
In both the contention-free and contention-based RA procedures, the UE transmits a preamble sequences on the RACH (msg1). In the contention-based mode, the preamble sequence is randomly selected by the UE from a set of available preambles sequences, which is periodically updated by the eNB. Conversely, in the contention-free mode, the preamble sequence is explicitly allocated either by the source eNB (for handover) or by the serving eNB (for downlink transmission).

After transmitting a preamble sequence, the UE monitors the PDCCH during a certain time, and, if no response is received, it enters a backoff period and then tries to transmit a new preamble sequence. This is repeated until the UE receives an RAR message or until the maximum number of preamble sequence transmissions has been achieved.

Upon detection of a preamble sequence, the eNB transmits an RAR message (msg2) on the PDSCH addressed to the Random Access Temporary Identifier (RA-RNTI), which is generated by using the preamble sequence index and the subframe in which the sequence was received. This message contains a timing advance command as well as an uplink grant for the transmission of a message in the following step. In the contention-free mode, upon receiving this message, the procedure is finished. To inform the UE about this transmission, a DCI message is allocated on the CSS region of the PDCCH to indicate the PDSCH resources in which the RAR message is transmitted. The number of RAR messages that an eNB can send is limited, e.g., three RAR messages per millisecond.

Once the RAR message is received by the UE, it transmits an L2/L3 message (msg3) on the Uplink Share Channel following the uplink grant contained in the received RAR message.

[1]In this paper, we use PDCCH to refer to enhanced PDCCH, MTC PDCCH and PDCCH itself.



(a) Contention-free

(b) Contention-based

Figure 1. Random-access procedure in LTE-A networks

This message will indicate the reason why the contention-based RA procedure was triggered. This message is addressed to the RA-RNTI and contains either the identity of the UE or a temporary UE identity. If two or more UEs chose the same preamble sequence in a certain random-access opportunity, they will receive the same grant in the RAR message, and, thus, all their L2/L3 message transmissions will collide. In such a case, after the maximum number of msg3 retransmissions is achieved, the UE re-initiates the Random Access procedure. When the number of RA attempts reaches a threshold, the network is considered unavailable by the UE, and an access problem exception is reported to the upper layers.

Finally, upon successful reception of an msg3, the eNB sends a Contention Resolution (CR) message (msg4) to the UE. Once the msg4 is successfully received by the UE, the contention-based RA procedure is finished.

III. Preamble Priority-Aware Control Resource Allocation Algorithm

This section describes the proposed Preamble-Priority Aware (PPA) algorithm for allocating PDCCH resources which aims at providing QoS differentiation by assigning different priority levels to RAR messages of different group of preamble sequences. Our proposal uses the PDCCH manager structure introduced in [5], which enables eNB to take into account RA-related messages in the PDCCH scheduling algorithm along with downlink assignments, uplink grants, and other control messages.

In the PPA algorithm, the groups of preamble sequences and their corresponding priority levels are based on the RA procedure and RAN overload control scheme defined by the Mobile Network Operator (MNO) at the eNB. This preamble differentiation provided by our proposal is quite important for HTC/MTC coexisting scenarios, which suffer from high blocking of RAR messages [4]. It is also of great relevance to provide some kind of QoS differentiation during the RA procedure since this procedure does not fully differentiate access of different users/devices [4].

The PPA algorithm defines three priority levels for the RAR messages: high, medium and low priority. The highest priority is given to RAR messages addressed to users utilizing the contention-free preamble sequences. This is justified by the fact that preambles in this group are generally used by users performing handover, which requires very low latency. Once the contention-free preamble sequences are prioritized, the contention-based preamble sequences are considered. Thus, the medium priority is for high-priority contention-based preambles as defined by the RA scheme or RAN overload control mechanism being used. For instance, there exist mechanisms that use an exclusive group of contention-based preambles to transmit very high priority messages such as Critical Alarm Messages [12]. Another example is the RRS scheme which divides contention-based preamble sequences into two groups to alleviate the effect of MTC on HTC. One is for HTC users and the other for MTC devices. In this case, the high priority set is the group of preamble sequences reserved to the HTC users. In HTC/MTC coexisting scenarios, RRS are used in conjunction with Access Class Barring (ACB) or Extended Access Barring (EAB) schemes. As the group of preamble sequences allocated to MTC users is not differentiated by any of these schemes, the second group of contention-based preambles dedicated to MTC users and low priority HTC users receives low priority by the PPA algorithm. When the traditional RA scheme is used (without using RAN overload control scheme), only the low and high priority levels are defined. After PPA algorithm processes all RAR messages, the msg4 messages and the other control messages are prioritized as in the RAP algorithm [5].

IV. Performance Evaluation

In this section, we evaluate the performance of the proposed PDCCH algorithm via extensive simulations by using the LTE-Sim simulator [13]. LTE-Sim is a discrete-event packet-level simulator developed in C++, widely used for simulating Medium Access Control functions of LTE/LTE-A networks. As our focus is on the RA performance under PDCCH constraints, actual data transmission is not used. We implemented both contention-free and contention-based operation modes of the RA procedure in the simulator as well as the proposed PDCCH mechanism. To alleviate the effect of MTC on HTC, the RRS RAN overload control scheme is also implemented in the simulator.

A. Simulation Model

Both HTC users and MTC devices are considered. Some HTC users are assumed to perform handover, which requires low access delays. As users performing handover were attached (in the connected state) to the source eNB, they use the contention-free RA procedure to establish connection with the target eNB [14]. The source eNB allocates a unique preamble sequence from a set reserved for this propose. Handovers follow a Poisson process [15] with mean μ. Voice-over-IP (VoIP) traffic, which has low delay requirements, is also employed. This traffic is modeled as explained in [13]. All VoIP users are assumed to use Semi-Persistent Scheduling with initial random-access [16]. This means that VoIP users initiate the RA procedure to send Scheduling Request (SR) messages at the beginning of each talkspurt. Other HTC traffic types such as video and File Transfer Protocol (FTP) are assumed to have uplink control resources allocated to send SR messages so that they do not frequently use RACH to request uplink resources. The interaction of MTC users with the Physical Random Access Channel (PRACH) follows the 3GPP MTC model, which assumes an extreme scenario with MTC transmissions highly synchronized modeled by the $Beta(3, 4)$ distribution in a 10 s interval [7]. As it is not feasible to periodically allocate Physical Uplink Control CHannel (PUCCH) resources simultaneously to several MTCs devices to send their uplink data [17], every time an MTC device needs to send uplink data it initiates the RA procedure.

A preamble sequence is successfully received with probability $1 - e^{-i}$, where i is the number of preamble sequence transmissions [7]. This assumption captures the effect of the power ramping technique and physical impairments of the PRACH channel. A UE device considers that a preamble sequence transmission has failed after pre-defined interval with no reception of the corresponding RAR message. Unlike the unrealistic assumption about preamble collision in the 3GPP MTC model [7], our simulation model considers that the eNB is not able to detect collision at the reception of the preamble sequence. Thus, two or more UEs can receive the same Packet Uplink Shared Channel (PUSCH) resources in the RAR message to transmit msg3 messages. In this way, collisions are only detected when a UE does not receive the msg4 message during a waiting window.

B. Simulation Setup

The simulation scenarios comprise a single cell with a 0.5 km radius. An eNB with 5 MHz cell bandwidth in the Frequency Division Duplexing mode is located at the center of the cell with several UE uniformly distributed around it. Each UE can act either as MTC devices or as HTC users. In addition, users performing handover are uniformly located at the cell edge. The number of HTC users in Radio Resource Control (RRC) connected state (active sessions), which are attached to the serving cell, is fixed to 100. We assumed that 40 percent of these users have VoIP traffic [18]. Based on the total number of RRC-connected devices, the mean number of X2 handovers (inter-eNB handovers) per second is 0.6 [19]. In order to account for intra-eNB handovers, we assume $\mu = 1.5$ handovers per second. HTC users move at a speed of 3km/h and follow the random walk mobility model whereas MTC users are supposed to be stationary. Simulations considered MTC scenarios with $5,000$ and $10,000$ MTC devices. We assumed that RA configuration parameters have already been received by the UEs in the beginning of the simulation. The downlink control channels use the first three Orthogonal Frequency Division Multiplexing (OFDM) symbols of every PRB, which corresponds to 20 CCEs for 5 MHz bandwidth. However, only 16 CCEs are available for the PDCCH [20]. Moreover, since all devices are uniformly distributed in the cell, an aggregation level of 4 CCEs per device is assumed [7]. The main configuration parameters used in the simulations are summarized in Table I.

TABLE I. SIMULATION PARAMETERS

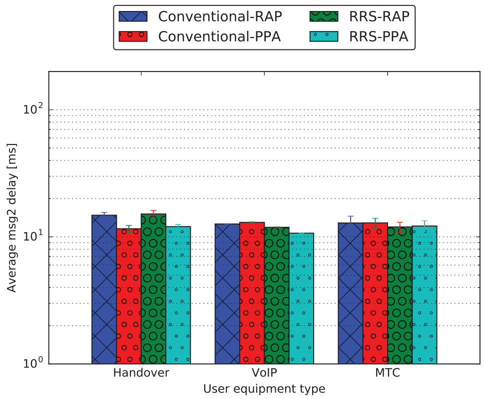
Parameter	Value
System type	Single cell
System bandwidth	5 MHz
Cell radius	0.5 km
PRACH configuration index	6
RA preamble format	0
Contention-free preambles	12
Contention-based preambles	52
Number of UL grants per RAR message	3
Number of CCEs allocated for the PDCCH	16
Number of CCEs per PDCCH	4
Backoff period	20 ms
HARQ retransmission probability	10%
preambleTransMax	10
Response Window Size	5 ms
Contention Resolution Timer	48 ms
maxHARQ-Msg3Tx	5
μ	1.5 handovers/s

C. Simulation Results and Discussion

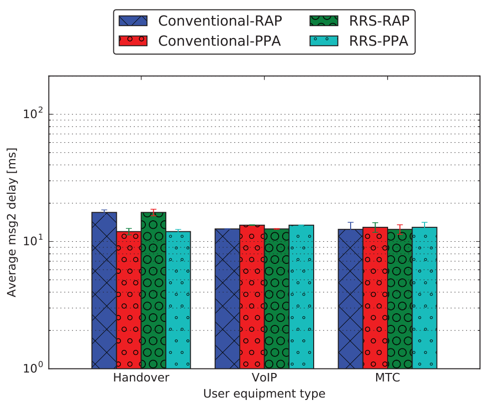
The figures presented in this section show mean values with confidence intervals of 95 % confidence level derived by using the independent replication method. All simulations were replicated 10 times with different seeds and the duration of each execution was 12.5 seconds. The metrics analyzed are the access success ratio, which is defined as the ratio of devices that successful perform the RA procedure; the average RA delay, which is the average time of execution of successful RA procedures; and the average msg2 delay, which is the time between the transmission of a preamble transmission and the reception of the RAR messages. The performance of the RAP and the PPA algorithms for the different type of UE are presented for both conventional LTE-A RA procedure and RRS scheme. The metrics are presented for scenarios with $5,000$ and $10,000$ MTC devices activated in the scenario.

Figure 2 shows the average msg2 delay. The average msg2 delays for VoIP users and MTC devices are quite similar. However, the PPA algorithm produces lower msg2 delays to user utilizing high priority preambles sequences (handover users) than does the RAP algorithm with both conventional RA scheme and RRS scheme. Moreover, this is achieved with a low increment in the msg2 message delays for the other users.

Figure 3 shows the average access delay. As expected, the access delays of handover users are shorter than those of the VoIP users and MTC devices. This is mainly due to the fact that handover users utilize contention-free RA procedure whereas the latter two users utilize contention-based RA procedure. For the UEs using contention-based RA procedure with $5,000$ MTC devices, access delays obtained by employing both RA schemes are quite similar, whereas

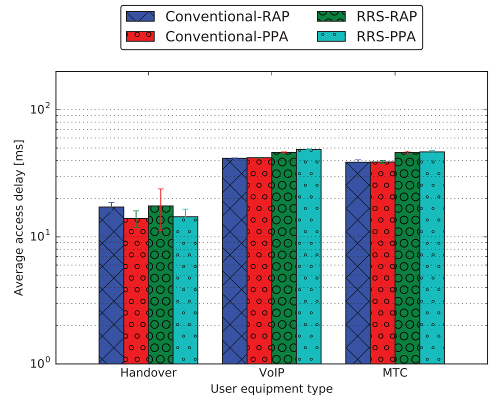


(a) $5,000$ MTC devices

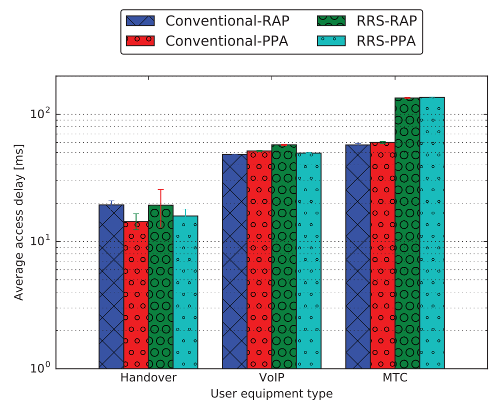


(b) $10,000$ MTC devices

Figure 2. Average msg2 delay



(a) $5,000$ MTC devices



(b) $10,000$ MTC devices

Figure 3. Average access delay

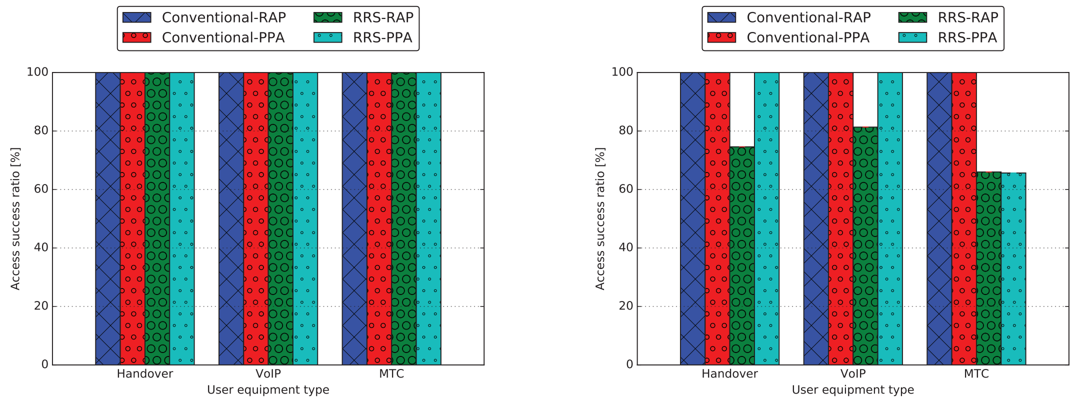
access delays given by the RRS scheme for $10,000$ MTC devices are larger than those given by the conventional RA scheme. This is because preambles sequences reserved for MTC devices are reduced, increasing the collision probability of these UEs. For handover users these values are quite similar to that of the msg2 delay because of the contention-free RA procedure used by these users. For users utilizing contention-based preambles sequences, the transmission of the msg3 message may collide when two or more users transmit the same preamble sequence, thus increasing the overall access delay. This collision is usually detected only when the msg4 message is not received by the UE. As the average access delay is calculated only for UEs which RA procedures are successfully finished, it cannot reflect further gain due to the use of a preamble-priority awareness approach in the PDCCH scheduling algorithm when high RACH collision and shortages of PDCCH resources sporadically occur.

To better understand this effect, Figure 4 shows the access success ratio. This metric value is 100 percent for all scenarios evaluated when $5,000$ MTC devices are activated in the simulations since enough resources exist for attending all type of users. However, for higher number of MTC devices, *i.e.*, $10,000$ MTC devices, when the RRS scheme is used with the RAP PDCCH scheduling algorithm, the access success ratio for handover and VoIP users are as low as 75 percent and 80 percent, respectively. This means that a portion of the users utilizing preamble sequences with high and medium priority are not able to get access to the network under massive number of access attempts. This occurs due to the shortages of PDCCH as a result of collision of MTC devices on the PRACH. Conversely, the preamble priority awareness approach of the PPA algorithm leads to no loss of access requests for users with high and medium priority levels. Thus, the PPA algorithm provides QoS differentiation during the RA procedure.

In summary, more important than the reduction of the access delay for UEs using prioritized preamble sequences, the use of the PPA PDCCH algorithm in coexisting MTC/MTC scenarios leads to no blocking of access requests from users utilizing prioritized preamble sequences. This is of great importance for incoming handover users, which require low latency and reliable access establishment with the network, and for HTC users such as VoIP users that generally have real-time QoS requirements. In addition, it can also provide the required support to emergency alarms.

V. Conclusion

In this paper, we have proposed a novel PDCCH resource allocation algorithm for LTE-A networks. This algorithm introduces the concept of preamble priority awareness for allocating PDCCH resources which allows UEs with prioritized preambles sequences to increase the chances of accessing the network and to reduce the access delay under heavy load in the



(a) $5,000$ MTC devices

(b) $10,000$ MTC devices

Figure 4. Access success ratio

PRACH. This is particularly useful for HTC/MTC coexisting scenarios, in which the radio resources are shared between these two and shortage of PDCCH and PRACH resources may occur because of the high number of devices. It is also relevant for user requiring low latency and access guarantees.

The Preamble-Priority Aware PDCCH scheduling algorithm prioritizes control messages derived from received preamble sequences by taking into consideration the priority of the preamble sequences as defined by the RA procedure and RAN overload control scheme being used by the mobile network operator. Simulation results show that the preamble priority-aware PDCCH scheduling algorithm is able to decrease random access delays while simultaneously achieving high access probability values for users whose preambles sequences are prioritized in the initial phase of the RA procedure such as user performing handover or HTC user executing real-time applications.

VI. Acknowledgements

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