Allocation of Control Resources for Machine-to-Machine and Human-to-Human Communications Over LTE/LTE-A Networks

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***Abstract*— The Internet of Things (IoT) paradigm stands for virtually interconnected objects that are identifiable and equipped with sensing, computing, and communication capabilities. Services and applications over the IoT architecture can take benefit of the long-term evolution (LTE)/LTE-Advanced (LTE-A), cellular networks to support machine-type communication (MTC). Moreover, it is paramount that MTC do not affect the services provided for traditional human-type communication (HTC). Although previous studies have evaluated the impact of the number of MTC devices on the quality of service (QoS) provided to HTC users, none have considered the joint effect of allocation of control resources and the LTE random-access (RA) procedure. In this paper, a novel scheme for resource allocation on the packet downlink (DL) control channel (PDCCH) is introduced. This scheme allows PDCCH scheduling algorithms to consider the resources consumed by the random-access procedure on both control and data channels when prioritizing control messages. Three PDCCH scheduling algorithms considering RA-related control messages are proposed. Moreover, the impact of MTC devices on QoS provisioning to HTC traffic is evaluated. Results derived via simulation show that the proposed PDCCH scheduling algorithms can improve the QoS provisioning and that MTC can strongly impact on QoS provisioning for real-time traffic.**

***Index Terms*—Long-term evolution (LTE), LTE-Advanced (LTE-A), machine-type communications (MTCs), packet downlink control channel (PDCCH) scheduling algorithm, random-access (RA) procedure.**

NOMENCLATURE

List of Acronyms

ACK	Acknowledgement.
3GPP	3rd Generation Partnership Project.
BSR	Buffer status report.
CN	Core network.
CBR	Constant bit rate.
DL	Downlink.
eNB	Evolved NodeB.
FTP	File transfer protocol.
GBR	Guaranteed bit rate.
H2H	Human-to-human.
HARQ	Hybrid automatic repeat request.
HTC	Human-type communication.
IoT	Internet of Things.
LTE	Long-term evolution.
LTE-A	LTE-Advanced.
M2M	Machine-to-machine.
MTC	Machine-type communication.
PDCCH	Packet downlink control channel.
PDSCH	Physical downlink shared channel.
PUSCH	Packet uplink shared channel.
PLR	Packet loss ratio.
PRACH	Physical random access channel.
PDB	Packet delay budget.
QoS	Quality of service.
QCI	QoS class identifier.
RA	Random access.
RACH	Random access channel.
RAN	Radio access network.
RRC	Radio resource control.
SR	Scheduling request.
UE	User equipment.
PUCCH	Physical uplink control channel.
PRB	Physical resource block.
DCI	Downlink control information.
CCE	Control channel element.
OFDM	Orthogonal frequency division multiplexing.
OFDMA	Orthogonal frequency division multiple access.
SC-FDMA	Single-carrier frequency division multiple access.
TTI	Transmission time interval.
FDD	Frequency division duplexing.
EAB	Extended access barring.
TDPS	Time-domain packet scheduling.
FDPS	Frequency-domain packet scheduling.
VoIP	Voice-over-IP.
HoL	Head of the line.
SRS	Sounding reference signal.
TPC	Transmit power control.
UL	Uplink.

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I. INTRODUCTION

IN THE past two decades, traditional cellular networks were mainly designed for H2H communication (HTC). However,

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with the development of the IoT, hundreds of billions of devices will access these networks. These massive number of M2M (MTC) devices will use cellular networks to support various applications of IoT.

The fourth-generation cellular networks based on LTE and LTE-A standards are key enabling technologies for the communication between machines without human intervention [1]. These technologies open up new business opportunities for mobile network operators given the expected growth in MTC as a consequence of the ever increasing deployment of sensors, smartphones, and wearable devices [2]. However, the introduction of a huge number of MTC devices poses a new set of challenges in the control of LTE/LTE-A networks, since traffic and service requirements of MTC differ from those of traditional HTC. Unlike HTC services, which typically demand high data rates, MTC services involve a massive number of devices transmitting small amounts of data, often with different requirements for reliability and availability. In H2H communications, congestion in the RACH is rarely a problem since the number of users requesting RA at the same time is usually not so large. However, the deluge of RA requests from the huge number of MTC devices may overload the network signaling resources. Such a pattern can result in the overload of the RAN, as well as congestion in the CN [3] of LTE/LTE-A networks. Such conditions can cause MTC services to affect the QoS provisioning for HTC services, and must, therefore, be addressed.

To overcome these problems, the 3GPP has proposed the EAB scheme [4] to be activated in overload conditions, thus avoiding increases the access delay when the RAN is lightly loaded [5]. A congestion coefficient indicates when the EAB scheme should be turned on [6], replacing conventional LTE RA scheme. Cheng *et al.* [5] showed that lightly loaded conditions, defined as a scenario with fewer than 5000 UEs, do not trigger the EAB scheme, and, consequently, the provisioning of QoS still relies on the traditional LTE RA scheme.

Previous work [7]–[10] has attempted to evaluate the impact of MTC services on QoS provisioning for HTC users. These papers have focused on either RA procedure or UL scheduling performance, which does not capture the effect that one mechanism has on the other, thus easily jeopardizing QoS provisioning. For example, if only the RA procedure is considered, the delay due to the use of the RA procedure can be high, leaving only a short period for the scheduling mechanism to act. This leads to violations of time requirements and consequent packet losses. Indeed, the delay due to the use of RA procedure and UL scheduling must be considered jointly to guarantee delay requirements. Moreover, a huge number of UEs employing RA procedure to obtain transmission opportunity will need resources for signaling on the PDCCH. The consumption of these resources will be significant and cannot be ignored by the scheduling mechanism, as would be possible if HTC services prevail since the PDCCH has limited resources. Indeed, this is the origin of the impact of MTC on QoS provisioning for HTC services in LTE networks. However, no previous paper has employed resource allocation mechanism in the PDCCH in conjunction with the RA procedure and both UL and DL scheduling.

This paper proposes a novel scheme for resource allocation on the PDCCH which considers the interaction of RA-related messages, UL grants, and DL assignments. This approach addresses the main issue of MTC in LTE networks. Moreover, PDCCH scheduling algorithms accounting for resources consumed by RA-related messages on the PDCCH and the PUSCH are introduced. To the best of our knowledge, this is the first study to evaluate the entire resource allocation process in LTE/LTE-A networks taking into account the contention-based RA procedure, as well as the impact of MTC on QoS provisioning.

This paper is organized as follows. Section II reviews the related work. Section III briefly introduces LTE technology, including contention-based RA procedure and control signaling required to perform resource allocation. Section IV describes PDCCH resource allocation management, and Section V introduces the novel QoS-aware PDCCH scheduling algorithms proposed. Section VI evaluates the impact of massive MTC devices on the QoS provisioning of HTC users and compares the performances of the proposed PDCCH scheduling algorithms. Finally, this paper is concluded in Section VII.

II. Related Work

This section presents a review of the literature related to the impact of MTC devices on HTC users, PDCCH resource allocation and MTC scheduling. Detailed description of RA schemes for CN congestion and RAN overload control can be found in [11]–[13].

A. Impact of M2M Communications on HTC Users

Zheng *et al.* [7] evaluated the impact of MTC on HTC and proposed two RA schemes; one gives priority to HTC devices and the other gives priority to MTC devices. The scenario evaluated was composed of 100 HTC users and from 100 to 60 000 MTC devices. MTC devices did not affect the blocking probability of HTC users, when the HTC services were prioritized. Furthermore, performance evaluation revealed only the effect of the RA procedure, and did not consider actual transmission of data.

In [10], we highlighted the impact of massive number of MTC devices on the access probability of HTC users. Moreover, we have shown that the access probability and access delay of both MTC devices and HTC users can be greatly affected when many MTC devices try to access the network simultaneously. However, this paper did not consider QoS requirements.

The influence of MTC on QoS provisioning in LTE networks was evaluated in [14], with voice, video, and FTP traffic used in the analysis. The traffic generated by MTC devices was composed of CBR sources with a packet size of 6 kB and a 60 s intertransmission interval. The number of MTC devices varied from 300 to 750 while the number of HTC users was fixed at 30. The bandwidth and QoS-aware UL scheduler [15] which provides delay and bit rate guarantees was employed in the simulations. Although the delay of real-time traffic (both voice and video) did not increase significantly with an increase

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in the number of MTC devices, the delay of non-real-time traffic (FTP) did. A shortcoming of this paper is that the effects of the RA procedure were not considered.

In [8], CBR packets with 100 bits were employed in a traffic model involving from 100 to 1 500 MTC devices and ten HTC users. The authors did not specify the interarrival interval, the UL scheduler or the RA scheme used in the simulations. They showed that the PLR of the HTC users increased as the number of MTC devices increased although the delay was not significantly affected. As in the previously mentioned paper, the RA procedure was not considered.

Various UL scheduling mechanisms for scenarios with MTC devices and HTC users have been proposed [11]. Almost all of them split the radio resources into two groups, one is for HTC users and the other for MTC devices. Gudkova *et al.* [9] proposed a framework to evaluate the performance of LTE UL channel, including radio resource allocation. Traffic generated by MTC devices involved a maximum number of PRBs allocated to MTC devices, whereas traffic generated by HTC users guaranteed a minimum number of them for this purpose. Although the control signaling overhead for resource allocation was taken into account, neither RA procedure nor PDCCH scheduling was considered. A comprehensive survey on UL scheduling for the support of MTC on LTE/LTE-A networks can be found in [11].

B. PDCCH Resource Allocation and Scheduling

Hosein [16] showed the performance of several PDCCH resource allocation algorithms. One is the baseline algorithm, which allocates control resources (i.e., the CCEs) on the basis of a priority queue of UEs to be scheduled. If the PDCCH scheduler cannot allocate resources for a given UE, that UE is blocked and the PDCCH scheduler continues to allocate resources for the next UE selected by the UL/DL scheduler. Another algorithm is resource shuffling, which attempts to find an allocation for a UE as in the baseline algorithm. With this algorithm, however, if an allocation cannot be made, the algorithm tries to reallocate all UEs that occupy one or more CCEs to liberate space. If the UEs can be reallocated, the new UE is placed on a currently empty resource. If no space can be emptied, the UE is considered blocked and the process is repeated for the next UE.

The above-mentioned algorithms allocate resources sequentially in the same order as prioritized by the UL/DL schedulers. In another approach, PDCCH resources are allocated on the basis of metrics independent of the priority assigned by the UL/DL scheduler. One algorithm using this approach is the minimum aggregation level [17], which sorts UEs in increasing order of priority order on the basis of the aggregation level.

C. Summary

None of the above-mentioned papers took into consideration the effect of MTC on QoS provided for HTC users. In some of them [8], [14], the performance evaluation of the packet scheduling did not consider the RA procedure. Moreover, no other paper addressed the joint use of PDCCH schedulers with RA-related messages for the allocation of control channel resources.

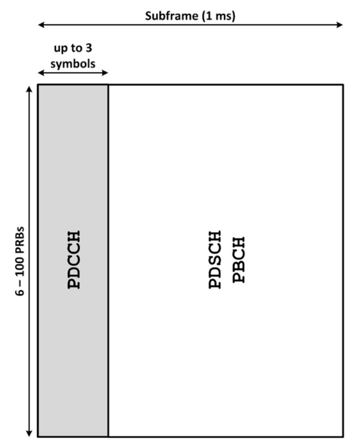

Fig. 1. Physical channels in DL.

In fact, the studies mentioned above do not allow the evaluation of massive number of MTC users on LTE/LTE-A networks, but rather are limited to an understanding of the influence of traditional LTE RA scheme on performance in the scenarios proposed by 3GPP. Another problem to be investigated is the identification of those aspect of scheduling (i.e., RA procedure, PDCCH scheduling and DL/UL packet scheduling) that most impacts the QoS provisioning in LTE/LTE-A networks.

III. LTE Background

This section provides some concepts in LTE/LTE-A networks necessary for the understanding of the proposed mechanisms, especially those related to PDCCH resource allocation and RA procedure.

A. Long Term Evolution

LTE/LTE-A networks are designed to support packet-switched with seamless mobility, QoS provisioning, and minimal latency. Transmissions in LTE are organized into radio frames of 10 ms, each frame divided into ten subframes of 1 ms. Subframes are divided into two slots of 0.5 ms. Transmissions are multiplexed using SC-FDMA in the UL channel, whereas OFDMA is used in the DL channel. The minimum amount of resources that a base station, called eNB, can allocate to a user is known as PRB, which is composed by two slots in the time domain and 12 contiguous OFDMA/SC-FDMA subcarriers which corresponds to 180 kHz in the frequency domain.

Resources are distributed between different channels (Figs. 1 and 2), on which either data or control messages can be sent. On the PDSCH data is sent in DL direction while on the PUSCH data is sent in the UL direction. The PDCCH carries control packets in the DL direction while the PUCCH carries control packets in the UL direction. Control packets on PDCCH carry the identification of the device to which the data/grants are for, which data/grants are sent, and how data are sent over the air on the PDSCH or PUSCH. The

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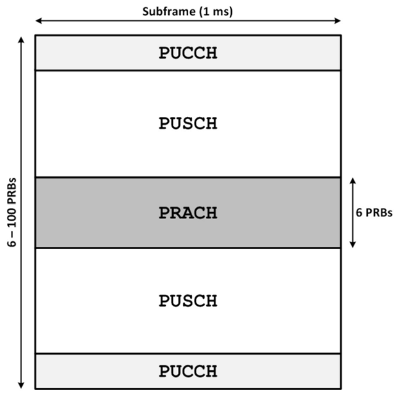

Fig. 2. Physical channels in UL.

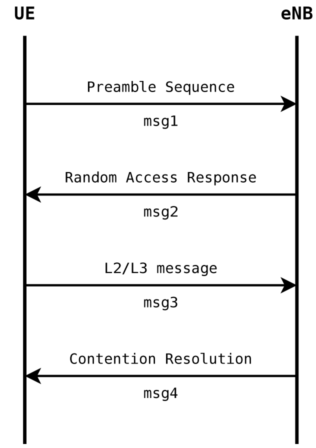

Fig. 3. Contention-based RA messages sequence.

PUCCH carries messages from UEs containing channel quality information, ACK, and scheduling request messages to the eNB. BSR and SR messages are used by UEs to require UL resources to transmit on the PUSCH. There is another channel called PRACH used to perform (re)connection, handover, and time synchronization by UEs. UE which are UL-synchronized send packets on PRACH to request UL resources when it does not have resource allocated on PUCCH or on PDSCH for transmission of BSR message. The packet scheduling executes resource allocation decisions every 1 ms, which is defined as the TTI.

The LTE QoS framework provides end-to-end QoS support in a per bearer basis. Users' flows are mapped onto one of two types of bearers, either GBR or non-GBR, and a QCI is assigned to each bearer. The difference between these two type of bearers is the support of QoS requirements, thus, a GBR bearer receives guaranteed data rate, while a non-GBR bearer does not.

B. Random-Access Procedure

In this section, the LTE/LTE-A contention-based RA procedure is described (Fig. 3).

In the first step, preamble sequence transmission (msg1), the UE transmits a randomly selected preamble sequence on the next available PRACH, from 64 orthogonally possible preamble sequences available for all the UEs. The eNB periodically broadcast information on the control channels on which preamble sequences can be used [18]. Collisions occur during the RA procedure if two or more UEs transmit the same preamble sequence on the same PRACH. However, since the eNB does not detect collisions by inspecting preamble signals interference, collisions are detected only in step 3.

In the second step, RA response transmission (msg2), the eNB sends a timing advance command for each successfully detected preamble sequence in the PRACH to all the UEs that transmitted a specific preamble sequence on that specific PRACH. Moreover, the eNB allocates UL resources to those UEs that sent the specific preamble sequence on a given PRACH for the transmission of the L2/L3 message in the step 3, which specifies the reason why the UE performed RA. If a UE which sent a preamble sequence did not receive an RA response from the eNB within a certain period of time or if it receives one not addressed to itself, an attempt for the next PRACH opportunity will be postponed. This can happen either due to preamble sequence collision or channel fading that has corrupted the response transmitted. The message msg2 is sent over the PDSCH, and the UE needs to receive a DL assignment control message over the PDCCH.

In the third step, L2/L3 transmission (msg3), the UE transmits a message on the PUSCH, using HARQ. The message is addressed to the temporary identifier of an RA response and carries either the identity of the UE, if it already has one, or an initial UE identity. If a preamble sequence collision occurs, two or more UEs will receive the same temporary identifier in the RA response, and, thus, will collide when transmitting their L2/L3 message. In this case, the UE reinitiates the RA procedure once the maximum number of retransmissions has been reached.

In the fourth step, contention resolution transmission (msg4), a contention resolution message is sent to the UE indicated by each L2/L3 message on the PDSCH. When collision occurs but L2/L3 message is successfully decoded, the HARQ request feedback is transmitted only by the UE which detected its own UE identity. The other UEs will understand that a collision occurred but transmit no feedback, thus aborting the current contention-based RA procedure and initiating another one.

C. PDCCH Functionality and Structure

The PDCCH and the other control channels occupy up to the first three OFDM symbols in a subframe with a normal cyclic prefix (Fig. 1). The overhead due to control channels can be adjusted based on the traffic scenario and channel conditions. The number of resources dedicated to the PDCCH is limited and it is approximately $4/5$ of the total available resources reserved to all control channels in DL, which depends on the total bandwidth of the system.

Resource allocation information is transmitted using DCI messages, which are the control messages carried by the PDCCH. These messages can be meant for a UE or group of UEs. The allocation of resources on PUSCH is determined on

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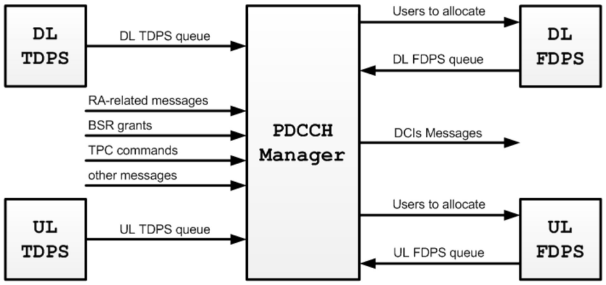

Fig. 4. Resource allocation functional architecture.

the basis of an UL scheduling process in the eNB. DCI messages are used by the eNB to indicate which PRBs the UE has been granted to use and what is the modulation and code scheme that should be used in the transmission. In addition, the eNB also schedules DL transmission on the PDSCH based on a DL scheduling process. DCI messages are also used to indicate which PRBs contain the DL data transmissions intended for a specific UE.

A PDCCH can contain several CCEs, which are the smallest amount of resources on PDCCH. A DCI message uses a certain number of CCEs to be transmitted, which depends on the UE's channel quality, bandwidth and number of OFDM symbols used by the control channels. The number of CCEs used to transmit a DCI message to a UE is known as aggregation level, which can be 1, 2, 4, or 8.

All transmission on PDCCH are modulated by quadrature phase-shift keying with a block error rate of 1%. DCI messages are usually located within the mainstream of the PDCCH but unknown to the UEs *a priori*. Thus, each UE applies blind decoding on a specified number of CCEs within two regions of the PDCCH, called common search space and specific search space. The set of these candidate CCEs is UE-dependent [19] and each UE performs this blind decoding to determine which, if any, contains its DCI message(s).

IV. PDCCH Resource Allocation Manager

The limited number of the CCEs available and the level of aggregation used can have a large effect on network performance. These aspects define how many DCI messages can be transmitted by a given eNB [20]. The PDCCH manager determines the number of CCEs used to transmit each DCI message during the TTIs, as well as the way of the DCIs messages are allocated on the PDCCH.

The interactions of the PDCCH manager [21] with UL packet scheduler, DL packet scheduler, and other entities are shown in Fig. 4. Packet scheduling is implemented in two (decoupled) steps, one in time domain and the other in frequency domain, which significantly reduces the scheduler complexity in frequency domain. The support of QoS requirements is also assumed to be controlled by the time domain scheduler, leaving the frequency domain scheduler to perform radio channel aware scheduling.

The PDCCH manager works in two steps, one to perform the scheduling and reservation of the CCEs on the PDCCH and other to assemble and delivery of the DCI messages.

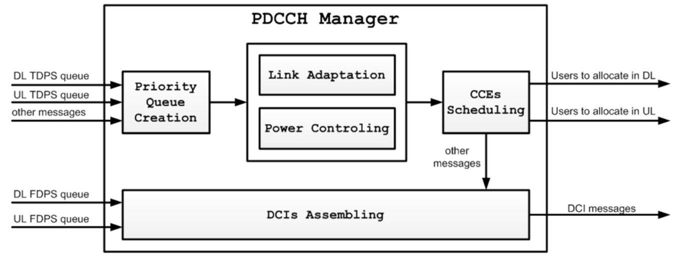

Fig. 5. PDCCH manager functional structure.

The first step consist of the following three tasks, as shown in Fig. 5. In the first task, priority queue creation, a priority queue with all DCI messages to be schedule by the PDCCH manager in the next TTI is created. This priority queue must consider not only UL grants and DL assignments but also all other control messages which must be scheduled on the PDCCH, such as RA-related messages (i.e., RA response message and contention resolution message), timing advance commands, and SRS commands. This approach is original and addresses the problem of MTC devices jeopardizing the QoS support to HTC users.

In this first task, UL grants and DL assignments are selected *a priori* by the UL TDPS and DL TDPS, respectively, and a priority queue is created either on the basis of the order of selection or the priority of each type of message.

The second task involves the assignment of the messages to a given number of CCEs (link adaptation) as well as assignment of a power offset (power control) so that the block error rate target can be met.

In the third task, the PDCCH manager involves the scheduling of the CCEs. The CCEs on the PDCCH are reserved as a function of the necessity of each message (i.e., aggregation level, search space, and transmission power). Resources are assigned first to the head of the priority queue; if no resource are available for that, the CCE scheduler moves to the next message in the queue. The messages in the priority queue are scheduled either sequentially, or in a way to find the best allocation of resources for each message independently of ordering. Here, the former approach, respecting the priorities of the messages in the queue, has been adopted.

After each message is processed, the PDCCH manager provides the queues to the FDPSs as well as information on which UEs that can be scheduled in the UL and DL directions. The FDPSs, then, allocate the PRBs on the UL/DL shared data channels.

In the second step, the PDCCH manager uses information on these two queues and selected UEs to assemble DCI messages for each UL grant and DL assignment and transmits all them on the PDCCH. Moreover, the RA-related messages can have their DCI messages assembled immediately after the CCEs Scheduling task finishes. After each DCI message is assembled, the PDCCH manager sends them on the PDCCH to the UEs.

V. PDCCH Schedulers

The PDCCH manager [16] considered only the priority level of the TDPS messages to create the priorized queue and

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neglected the RA-related messages and the other control messages in LTE/LTE-A. In this paper, however, the exchange of RA-related messages is included with the other control messages such as UL grant, DL assignment, timing advance command, and SRS request command.

Once the priority queue is created, the PDCCH manager starts link adaptation and power control assignment for each DCI, and then undertakes CCE scheduling.

The throughput of an LTE network depends not only on the packet scheduler algorithms themselves but also on the strategy of PDCCH resource scheduling. In each subframe, only a single RA response message can be transmitted, employing three UL grants for the RA msg3 [3].

The limitation of PDCCH resources can lead to an increase in transmission delays experienced by the UEs, and consequently, the degradation of QoS for real-time services. One efficient way of avoiding such degradation is to take the delay and deadline of each message into consideration.

In this section, we propose three novel standard-compliant PDCCH scheduling algorithms to create priority queues for guaranteeing QoS requirements on the PDCCH. These algorithms require that the packet scheduling is implemented in a decoupled way (Fig. 4).

A. RA-Priorized Algorithm

In this algorithm, decreasing levels of priority are given to the following messages: RA response message, contention resolution messages, BSR grants, TPC commands, DL assignments, and UL grants. The order of priority of the UL grants and DL assignments received from UL/DL TDPSs are maintained by the PDCCH scheduler in the assignments of priorities.

B. Lifetime-Aware Algorithm

The lifetime-aware (LTA) algorithm follows the LTE/LTE-A specification and employs QoS-related metrics to prioritize DCIs for scheduling.

In this algorithm, the level of priority is determined by the ratio between the delay experienced by the messages and the maximum delay allowed. To do this, we defined the metric δ to measure how close the lifetime of the message is to the deadline, and it is shown as follows:

$$\delta = \frac{\text{experienced delay}}{\text{maximum delay bound}}. \quad (1)$$

First, the algorithm calculates the metric value of each control message with pending transmissions to define the priority level, then the control messages are sorted in a decreasing priority order. When δ is close to 1 the control message has high priority since its delay is close to the maximum delay allowed.

For the RA response message, the delay experienced is the time elapsed since the creation of the message, and the maximum delay bound is equal to the maximum time that the UEs can wait for an RA response message (ra-ResponseWindowSize) [22]. The delay experienced by the contention-resolution message is the same as that of an RA response message while the maximum delay bound is equal to the maximum time that the UEs can wait for contention-resolution message (mac-ContentionResolutionTimer) [22].

The delay for the BSR grants, that are transmitted in response to the SR messages, is the time elapsed since the creation of the grant while the maximum delay bound is equal to the value of mac-ContentionResolutionTimer.

The delay experienced by DL assignments and UL grants is the delay of the HoL packet of the bearers buffer of the UE and the maximum delay bound is the PDB of the corresponding bearer, which depends of the QCI assigned to that bearer.

C. GBR-Priorized LTA Algorithm

In this algorithm, messages are classified into two groups, one for RA-related messages, BSR grants, TPC commands, and both DL assignments and UL grants of GBR bearers (GBR group), and the other for DL assignments and UL grants of non-GBR bearers (non-GBR group).

This algorithm creates these two groups by: 1) checking the type of bearer in each message (the QCI value is used to separate the two groups); 2) utilizing the metric δ in (1) for each group in order to set the priority level of each DCI; and 3) sorting the DCIs in each group in a decreasing priority level order. Once groups are created, the GBR group get priority over the non-GBR group, so that the former are scheduled before the latter.

VI. Performance Evaluation

Evaluation of the proposed scheme employed simulation using the simulator LTE-Sim simulator [23], which is an event-driven packet level simulator developed in C++ and widely used for simulating the medium access control of LTE/LTE-A networks. We implemented the contention-based RA procedure, the padding and regular BSR, the PDCCH management, the two-stage approach for the packet scheduling [24] and QoS support for UL transmissions in the LTE-Sim simulator.

A. Simulation Model

The simulation scenarios are composed of single cells with a 0.5 km radius. At the center of each cell, a single eNB with several UEs (both HTC users and MTC devices) uniformly located around it. All the UEs are created at the beginning of each simulation.

The cell bandwidth is 5 MHz in the FDD mode. The UL bandwidth is divided into 25 PRBs as specified in the standard [18]. The PUSCH consists of 24 PRBs, used for UE data transmission, with the remaining PRB reserved for the PUCCH. The PRB used by PUCCH is located at the beginning and at the end of the spectrum to ensure contiguity of available PUSCH resources. The DL control channels are configured to use the first three OFDM symbols of every PRB (which corresponds to 20 CCEs). However, since only $4/5$ of the total number of CCEs available will be used by the PDCCH [25], 16 CCEs are allocated for this channel. Moreover, since all UEs are uniformly distributed in the cell, an aggregation level of two CCEs per UE is assumed with the same transmission power for all CCEs. Since only UL

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traffic was implemented, for every UL grant message scheduled by the PDCCH scheduler, a DL assignment is assumed to occur [26].

UEs are assumed to be in the RRC connected state. Both padding and regular BSRs are configured to be sent. A regular BSR is triggered when data arrives at an empty UE radio bearer buffer. When a UE does not have UL resources for transmission of the regular BSR on the PUSCH, the UE triggers an SR. Since it is not feasible to periodically allocate PUCCH resources simultaneously to several UEs [27], when a UE needs to send an SR and there is no available PUCCH resources for the SR transmission, the UE initializes the RA procedure. If more than one UE chooses an identical preamble sequence in the same RA opportunity, these sequences collide at the eNB. The reception of a preamble sequence by an eNB then depends on the transmission power of the UE. Consequently, power ramping is used to gradually increase the transmission power so that specific channel conditions are met. To take power ramping into account, the preamble sequence is assumed to be successfully received with the probability $1 - e^{-i}$, where i is the number of transmission attempts, as recommended by the 3GPP [4].

Table I shows the configuration parameters used in the simulations as well as the parameter values used for the RA procedure [4].

HTC users transmit VoIP, video, and CBR traffic. For every two HTC users transmitting VoIP traffic and two HTC users transmitting video traffic, there is only one HTC user transmitting CBR traffic. MTC devices are assumed to be using a single type of traffic, allowing the simulation of scenarios with a large number of MTC devices trying to transmit in a highly synchronized manner [28]. The first transmission time for the MTC devices follows a Beta(3,4) distribution in an 10 s interval [28].

VoIP traffic uses semipersistent UL scheduling [29], so that the resources on the PUSCH are allocated periodically, without the need for the eNB to send UL grants on the PDCCH. Scheduling on the PUSCH is performed every 20 ms after the first transmission. For all UEs transmissions (excluding VoIP users), one byte is used to convey a padding BSR message.

HTC users are considered to move at a speed of 3 km/h and follow the random walk mobility model, while all MTC devices are stationary. VoIP and video traffics use GBR bearers, whereas best effort (modeled as CBR) and MTC traffics use non-GBR bearers. For the traffic on GBR bearers, when the delay of a packet is greater than the PDB value, the packet is dropped. This packet drop process is performed for each TTI by the UE at the beginning of UL transmission. Information about the delay of the HoL packet of each bearer is assumed to be available in each TTI at the eNB. To avoid intrauser scheduling interference, each UE is assumed to have a single bearer and the traffic of a single class. Table II summarizes the traffic models used in the simulations.

The following metrics were considered in the analysis: the total throughput of the network, considering the traffic of all UEs in that network (aggregated throughput), the fraction of the PRBs allocated (PRB utilization), the fraction of the CCEs allocated (CCE utilization), the percentage of dropped packets (PLR), the ratio between the number of unsuccessful completions of the RA procedure and the total number of RA procedure attempts (RA blocking probability), the delay between traffic arrival time and successful completion of the RA procedure (RA delay), and the delay between the time the packet enters in radio link control queue and that when it successfully arrives at the eNB (end-to-end delay).

The performance of the PDCCH schedulers was evaluated for various different packet schedulers, as well as for the conventional LTE RA scheme. Three different schedulers were used: 1) the maximum throughput (MT) [30]; 2) the proportional fair (PF) [31]; and 3) the Z-based QoS (ZBQoS) [24] schedulers, which have different characteristics: they are channel-aware, fairness-aware, and QoS-aware, respectively. This makes possible to evaluate the effect of the proposed PDCCH schedulers with the most frequently employed packet scheduling classes in LTE/LTE-A networks.

The simulations assessed the performance of the proposed PDCCH schedulers as well as the impact of MTC devices

TABLE I
SIMULATION PARAMETERS

Parameter	Value
System type	Single Cell
Cell radius	0.5 km
Channel model	Macro-Cell Urban Model
Number of HTC users	25
Number of MTC devices	0 to 2,000
Mobility model	Random Walk (3 km/h)
System bandwidth	5 MHz
Number of PRBs in the PUSCH	24
Carrier frequency	2 GHz
Frame structure	FDD
TTI duration	1 ms
Uplink schedulers	TD: ZBQoS; FD: PF-FME TD: PF; FD: PF-FME TD: MT; FD: MT-FME
Max. number of UEs passed to the PDCCH Manager	5
RA procedure	contention-based
PRACH Configuration Index	6
Preamble sequence format	0
Max. preamble sequences retransmissions	10
Number of uplink grants per RA response	3
Total preamble sequences	52
ra-ResponseWindowSize	5 ms
mac-ContentionResolutionTimer	48 ms
Backoff indicator	20 ms
Retransmission probability for msg3	10 %
Max. number of msg3 retransmissions	5
PDCCH CCE resources	16
PDCCH aggregation level for Msg2	8 [3]
PDCCH Aggregation level for Msg4/UL grant/DL assignment	2

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TABLE II
TRAFFIC MODEL AND QoS REQUIREMENTS

Traffic	VoIP	Video	CBR	MTC
Description	G.729 ON/OFF Model	H.264 Trace-based[a]	500 Bytes every 16 ms	125 Bytes every 5 s
Bit Rate	8.4 kbps	128 kbps	250 kbps	200 bps
QCI	1	2	8	9
PDB	100 ms	150 ms	300 ms	300 ms
GBR	8.4 kbps	128 kbps	N/A	N/A
Proportion	2 (40%)	2 (40%)	1 (20%)	N/A

[a] We use the trace of the video Foreman; it is available in LTE-Sim [23].

TABLE III
DELAY METRICS FOR THE VIDEO TRAFFIC
USING THE ZBQoS SCHEDULER

Metric [ms]	Alg.	Number of Active MTC devices 0	250	500	1000	1500	2000
End-to-end delay	A	39	40	42	45	61	68
	B	40	41	42	48	55	58
	C	39	40	42	45	60	66
RA average delay	A	33	35	37	41	43	43
	B	33	35	38	44	50	55
	C	33	35	37	40	42	43
RA delay 95^{th} percentile	A	82	88	100	111	118	121
	B	82	89	98	116	132	153
	C	79	88	101	111	115	121

A - RAP
B - LTA
C - GBR-LTA

on the QoS provisioning for HTC users when the conventional LTE RA scheme (without overload control mechanism) is used. In order to do this, the number of active MTC devices was varied from 0 to 2000, based in lightly-loaded scenario [5].

B. Simulation Results and Discussion

Figures in this section are mean values, with confidence intervals corresponding to a 95% confidence level derived using the independent replication method. Each replication simulated 11 s of the scenarios employed. All metrics evaluated are presented as a function of the number of active MTC devices in the cell.

Fig. 6 illustrates the PLR of video, CBR, and MTC traffic for the PDCCH schedulers proposed. The packet loss ratio produced by the PDCCH schedulers for video traffic increases as the number of active MTC devices increases [Fig. 6(a), (d), and (g)]. This trend can be better understood when access delay is taken into consideration. Even though both end-to-end delay and RA delay values (Table III) are quite low (around 50 ms) for all PDCCH schedulers, the 95th percentile for RA delays (Table III) reveals delays in the range of 80 to 130 ms, which is quite high for video traffic and can lead to packet loss. For example, an SR with an access delay of 130 ms leaves (ignoring backhaul and core network delays) the UL packet scheduler roughly 20 ms to provide resources to UEs, if 150 ms is assumed to be the delay bound for video traffic. In such scenarios, packets are likely to be dropped before the UE device receives the corresponding UL grant to transmit them. This situation generated a large packet loss experienced by video traffic.

The QoS awareness approach of the ZBQoS packet scheduler leads to less packet loss than those produced by the PF and MT packet schedulers. The LTA and GBR-priorized LTA (GBR-LTA) algorithm produced lower PLR values than does the RA-priorized (RAP) algorithm when jointly used with the ZBQoS packet scheduler. This happens since both resource allocation for control messages (on the PDCCH) and UL data packets (on the PUSCH) take into consideration the corresponding delay bounds.

As the MT scheduler allocates resources considering only the channel quality instead of QoS requirements, packet loss of video traffic produced by this scheduler significantly increases with the increase of the number of MTC devices. The PLR produced by the LTA PDCCH scheduler is much lower than that produced by the RAP and GBR-LTA PDCCH schedulers, when used jointly with the PF packet scheduler.

Despite the fact that the PLR of video traffic surpasses 1%, the use of the LTA algorithm leads to no loss of CBR traffic when used either with the PF scheduler or with the ZBQoS scheduler [Fig. 6(e)], as a consequence of the large PDB requirement of CBR traffic and the use of BSR padding messages. These packet schedulers provide scheduling policies with distinct objectives; the PF packet scheduler maximizes the fairness among users whereas ZBQoS packet scheduler guarantees QoS requirements. Although MTC traffic has similar QoS requirements than that of the CBR traffic, the RA procedure for a large number of MTC devices are performed in a coordinated way, which generates packet losses. Since CBR traffic rarely performs RA procedure (due to the use of BSR padding messages) and the access of CBR traffic is performed in an uncoordinated way, the impact of RA-related issues is reduced which leads to better performance even when the QoS requirements of the CBR traffic are similar to those of the MTC traffic.

PLR values for CBR and MTC traffic increase sharply after 1000 MTC devices are included, since the QoS-awareness of the ZBQoS packet scheduler gives low priority

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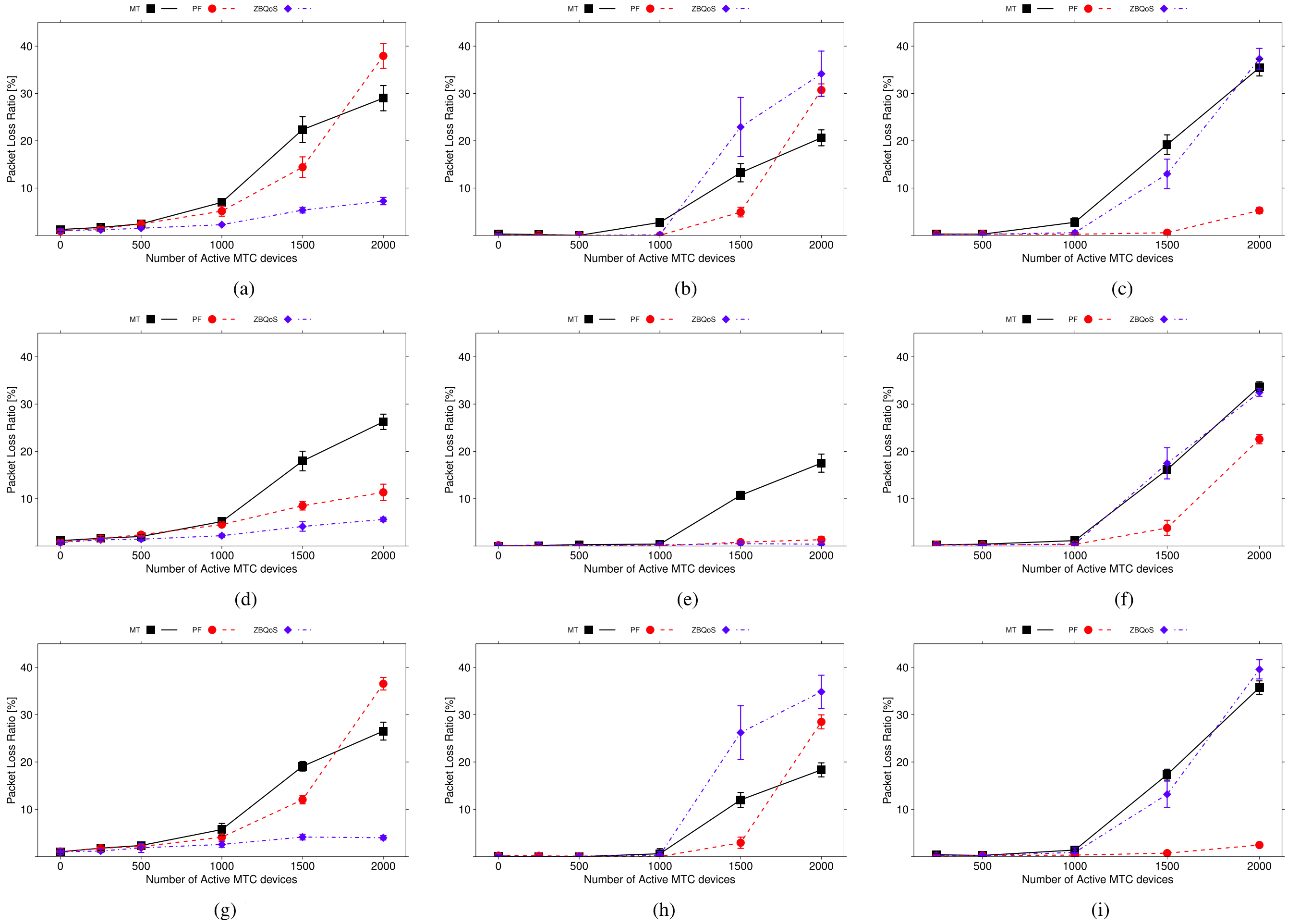

Fig. 6. Effect of the number of active MTC devices on the PLR for the proposed PDCCH schedulers with different packet schedulers. (a) Video traffic—RAP. (b) CBR traffic—RAP. (c) MTC traffic—RAP. (d) Video traffic—LTA. (e) CBR traffic—LTA. (f) MTC traffic—LTA. (g) Video traffic—GBR-LTA. (h) CBR traffic—GBR-LTA. (i) MTC traffic—GBR-LTA.

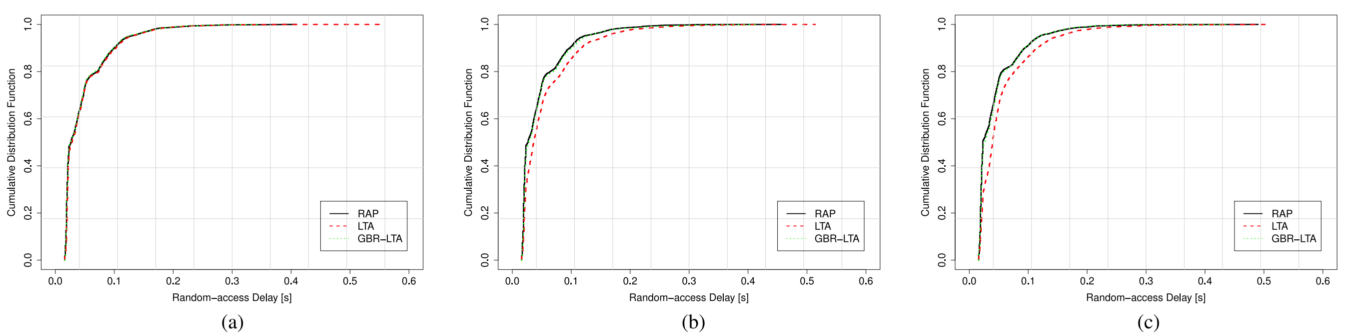

Fig. 7. CDF of RA delays of video users for scenario with 2000 MTC devices. (a) MT. (b) PF. (c) ZBQoS.

to non-real-time traffic. When the MT and PF packet schedulers are used, this effect is eliminated in some scenarios [Fig. 6(c), (e), and (i)]. MTC traffic is affected by almost all combinations of PDCCH and packet schedulers, mainly due to the large number of active MTC devices. The use of RAP or GBR-LTA algorithm in conjunction with the PF packet scheduler were able to produce low PLR values for MTC devices. However, these are also the ones that produced the highest PLRs values for HTC traffic (i.e., video and CBR). PF scheduler gives high priority to MTC traffic because interarrival intervals are much longer than the window size for measuring the rate provided to devices, which typically is in the order of tens or hundreds of milliseconds. In this way, MTC devices always obtains high priority in the first transmission request after a long period without transmitting packets (while the PDCCH schedulers give high priority to RA-related control messages).

The end-to-end delay values of video traffic produced by all proposed PDCCH schedulers with the ZBQoS packet scheduler slightly increase with the increase in the number of active

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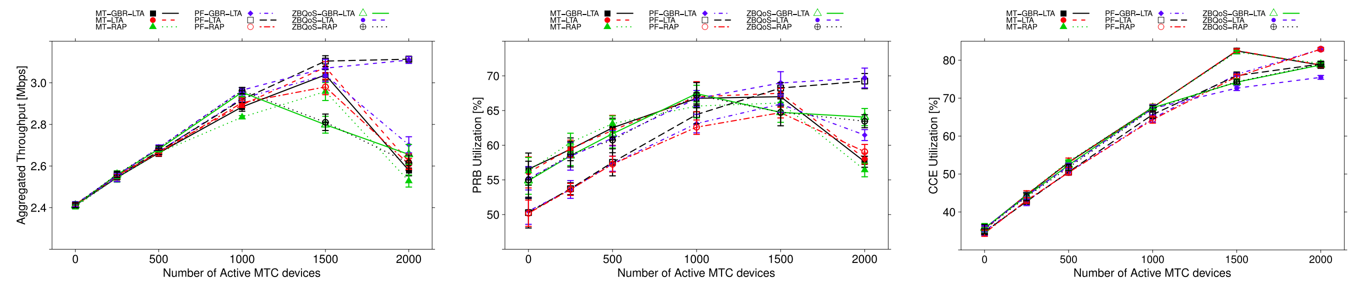

(a) (b) (c)

Fig. 8. Effect of the number of active MTC devices on resource utilization. (a) Aggregated throughput. (b) PRB utilization. (c) CCE utilization.

MTC devices (Table III), however, the values are around 50 ms, which is considered a low value for video traffic. Although the LTA algorithm produces the lowest end-to-end delay values, it is the one that provides the highest 95th percentile RA delay values, especially for a large numbers of MTC devices. This happens since the LTA algorithm puts all control requests together. As more MTC devices access the network, the time consumed by the PDCCH scheduler to schedule RA-related messages for video users increases.

PLR and end-to-end delay of VoIP traffic are close to zero (figures not shown in this paper). This occurs because semipersistent scheduling is employed for VoIP users, which performs a periodic reservation of PRBs for these users. Having this reservation, VoIP users do not use PDCCH or PRACH resources in order to obtain PUSCH resources. RA blocking probability values for all scenarios are also close to zero (not shown here). This means all RA procedures initialized by the UEs were successfully finished.

Fig. 7 shows the influence of the proposed PDCCH algorithms on the RA delay produced by different packet schedulers for video traffic. RA performance of the MT scheduler does not change much regardless of the PDCCH schedulers employed. However, RA delay for both PF and ZBQoS schedulers slightly increases when the LTA algorithm is employed. The low PLR produced by these packet schedulers [Fig. 6(d) and (e)] increases the amount of CBR and video traffic control messages, leading to large delays experienced by the RA-related messages.

Fig. 8 shows the effect of the number of MTC devices on resource utilization on both PDCCH and PUSCH. The aggregated throughput values produced by different schedulers is almost the same [Fig. 8(a)] given all combination of PDCCH and packet schedulers, although it increases slightly until the level of 1500 MTC devices is reached as a consequence of the number of packets transmitted by these devices, after that, the aggregated throughput decreases slightly due to the massive competition between MTC devices. PRB utilization also increases until 1500 MTC devices, at this point, it starts to decrease for some schedulers. Such trends in aggregated throughput and PRB utilization are a consequence of packet loss (Fig. 6). When the packet loss of video and/or CBR traffic decreases, the PRB utilization increases. Since MTC devices use few PRBs, a high packet loss of MTC devices does not affect either PRB utilization nor aggregated throughput.

The CCE utilization increases as the number of active MTC devices increases [Fig. 8(c)] for almost all combinations of PDCCH and packet schedulers, reaching 80% when there are 2000 MTC devices. This is a consequence of resource consumed by the RA-related messages and control messages for data transmission on the PUSCH and data reception on PDSCH. The increase in consumption of control resources is one of the main problems when massive number of MTC devices shares the cell with HTC users. For MT scheduler, the CCE utilization slightly decreases after 1500 MTC devices due to the high PLR for all scenarios (Fig. 6).

Neither the control nor UL packet channels were congested in these lightly-loaded scenarios as adequate resources for control and data transmission were available [Fig. 8(b) and (c)]. Therefore, the packet loss that occurs (Fig. 6) is due to the RA procedure on the PRACH. This is particularly important since several proposed schedulers [11] for the support of MTC assumed that there are not enough resources on the PUSCH, and as a consequence adopted the splitting of PRBs into two groups, one for MTC devices and the other for HTC users. This approach is useful only if the PUSCH is congested. When resources on the PUSCH are available, such approach can lead to unwanted packet losses of HTC traffic.

These results show that control resource allocation is quite important for the coexistence of HTC and massive MTC under the same cellular network infrastructure. Depending on the traffic type, different combinations of PDCCH and packet schedulers should be used. For example, if the mobile network operator goal is to support QoS requirements to real-time users, the GBR-LTA PDCCH scheduler should be used in conjunction with a QoS-aware packet scheduler. If the goal is to provide reliable MTC, a fairness policy should be used in the packet scheduler together with the GBR-LTA PDCCH scheduler. Conversely, the LTA PDCCH scheduler combined with either a fairness-oriented or a QoS-aware packet scheduler should be used to maximize network utilization when there is a massive number of MTC devices.

VII. Conclusion

This paper has introduced a novel scheme for resource allocation on the PDCCH of LTE/LTE-A networks. This scheme allows priorization of control messages on the basis of the combination of control messages, e.g., RA-related messages,

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BSR grants, TPC commands, UL grants, and DL assignments. Novel PDCCH schedulers that utilize the proposed scheme have also been proposed. One priorizes RA-related messages while the others introduce QoS-awareness, which is relevant in MTC scenarios. Simulation results show that the QoS-aware PDCCH schedulers in conjunction with QoS-aware packet schedulers are able to improve QoS provisioning to real-time traffic in scenarios with both MTC devices and HTC users.

RA procedure plays an important role in resource allocation in LTE/LTE-A networks with support to M2M communication. In fact, it was found that RA delay strongly impacts QoS provisioning for real-time users under lightly-loaded MTC scenarios. Such provisioning, however, can be jeopardized as a consequence of the use of massive number of MTC devices simultaneously trying to access the network. Therefore, this paper presents a relevant step toward the deployment of the IoT over LTE/LTE-A networks.

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