Impact of M2M Traffic on Human-type Communication Users on the LTE Uplink Channel

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***Abstract*—The worldwide markets for Machine-type Communication (MTC) over cellular networks are expected to grow in the incoming years. However, since MTC is quite different than existing Human-type Communication (HTC), it poses significant challenges to the cellular networks. Large number of MTC devices are anticipated to be operating in the future Long Term Evolution (LTE) networks, bringing several service requirements. The LTE standard suffers from excessive Physical Downlink Control Channel (PDCCH) overhead associated with the radio resource allocation method for small, sporadic traffic per terminal which is the nature of Machine-to-Machine (M2M) traffic. The rigid Quality of Service (QoS) support framework of LTE for voice and data services also fails to address specific QoS requirements of M2M traffic. This paper focuses on describing the impact of M2M traffic on the performance of the HTC users in LTE Frequency Division Duplexing (FDD) uplink. Simulation results show the impact of M2M traffic on the performance of different types of Human-to-Human (H2H) services (Voice-over-IP (VoIP), video and CBR), when using a QoS-aware packet scheduling. Although MTC in LTE networks impacts HTC, the utilization of a semi-persistent scheduling scheme to VoIP traffic can reduce such impact.**

Keywords*—*Long Term Evolution, Machine-type Communications, Human-type Communications and Semi-persistent scheduling.

I. INTRODUCTION

The future telecommunication networks is envisioned to be largely influenced by Machine-type Communication (MTC). The major challenges to enable a truly networked society involve the massive growth in the number of connected devices and an increasingly wide range of applications with diverse requirements and characteristics. The number of human-centric communication devices is predicted to be exceeded tenfold by communicating machines in the future. Consequently, one of the key drivers for further evolution of Long Term Evolution (LTE) radio access technology is the support of MTC [1].

MTC enable various network-accessible devices to communicate with remote applications for monitoring and control of different environments. Machine-to-Machine (M2M) applications encompass a wide range of use cases such as smart grids, smart cities, surveillance systems, asset tracking, e-Health, connected consumers, Intelligent Transportation System (ITS), industrial automation and so on. Besides that, the increased usage of smart devices in daily life also involves automatic background data exchanges by large number of devices, which adds load to the networks [2].

In despite of the capacity and wide coverage that LTE networks can offer to M2M traffic, resource scheduling strategies and LTE channels were designed for Human-to-Human (H2H) traffic. Such design is reflected in the classes of the Quality of Service (QoS) supported by LTE [3], which includes Guaranteed Bit Rate (GBR) and non-GBR traffics. Moreover, M2M traffic is different from the traditional voice and data traffic for which most of the existing networks, including LTE, are optimized. M2M traffic are more intense in the uplink direction than in the downlink direction [4]. Therefore, the successful deployment of MTC in LTE networks requires an optimum scheduling policy to maximize the uplink channel capacity for a massive number of MTC devices as well as to satisfy the M2M specific requirements in terms of packet delay tolerance, jitter and loss, with minimum control signalling exchange. The sensors are typically (but not always) static and does not require to be optimized for mobile use. A massive number of machines may exist in a cell, accessing the network periodically or in random bursts. These machines have limited power that should be used as efficiently as possible, and they may need a very small portion of the network resources at a time, but as the number of machines is growing, their total resource demand can overwhelm the network very easily, e.g, the Radio Access Network (RAN) may not be able to handle the momentary surge in Random-access (RA) requests if thousands of devices perform RA attempts at the same time.

Most downlink and uplink scheduled data transmissions have to be signaled by the evolved NodeB (eNB) in the Physical Downlink Control Channel (PDCCH) beforehand, defining the shared resources to be used by a connected User Equipment (UE) for data reception/transmission [5]. However, the number of control resources is limited as well as depends on the PDCCH and bandwidth configurations. Such system design is suitable for human end-users because the data channel resources consumed by each user are sufficiently large and users usually require specific continuous bit rate. On the contrary, data resource consumption per MTC device is typically small (M2M traffic payload size is small) and not frequent. As a result, despite the data channel providing enough resources to accommodate M2M traffic, the LTE system is likely to be limited by the control channel capacity when it comes to support large number of MTC devices [6].

The objective of this paper is to show the impact of M2M traffic on the Human-type Communication (HTC) users performance in the uplink direction with a QoS-aware packet scheduling [7] when a realistic PDCCH design is taken into account.

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The remainder of this paper is organized as follows. Section II reviews related work. Section III introduces an overview of MTC in LTE networks. Section IV outlines the general PDCCH. Section V details the three scheduling schemes: persistent, dynamic and semi-persistent. Section VI evaluates impact of the MTC in HTC using different scheduling schemes. Finally, the paper is concluded in Section VII.

II. RELATED WORK

In our previous work [2], the impact of massive number of MTC devices on the access probability of HTC users was highlighted. In that study, we showed that the access probability and access delay of both MTC devices and HTC users can be greatly affected when several MTC devices try to access the network simultaneously. It evaluated different Random-access schemes proposed by the 3rd Generation Partnership Project (3GPP). However, our previous work neither considers actual data transmission nor QoS requirements.

In [8], two new Random-access schemes were proposed and evaluated. One scheme prioritizes HTC users and the other gives high priority to MTC devices. It was shown that MTC devices do not affect the blocking probability of HTC users when high priority is given to HTC users. However, just as in [2], this work revealed only the effect of the Random-access procedure since it did not consider actual data transmission.

The influence of M2M traffic on QoS provisioning was evaluated in [9], using different applications. A QoS-aware uplink scheduler proposed for H2H traffic was used in the study, providing delay and bit rate guarantees to QoS-sensitive applications. It was shown that the delay of non-real-time traffic significantly increased with an increase in the number of MTC devices whereas the delay of real-time traffic was not affected. Although this study considers actual data transmission, it does not take into account the effects of the random-access procedure and PDCCH scheduling on performance.

In [10], the performance of an LTE network was evaluated, considering a scenario with both HTC users and MTC devices. Authors showed that the packet loss ratio of HTC users increased as the number of MTC devices increased although the delay was not significantly affected. As in the previously mentioned paper, the Random-access procedure and PDCCH scheduling were not considered.

A comprehensive survey on MTC uplink scheduling for LTE/LTE-Advanced can be found in [11] in which various M2M-specific uplink packet scheduling are described. Typically, the data channel resources are split into two groups, one is for HTC users and the another for MTC devices. For example, in [12], MTC devices have a maximum number of Physical Resource Blocks (PRBs) allocated to them, whereas a minimum number of uplink resources are reserved to exclusive use of HTC users. Although the system model used in this work considers the control overhead introduced by PDCCH, it neither considers Random-access procedure nor PDCCH scheduling.

In summary, none of the above mentioned papers took into consideration the joint effect of packet scheduling, PDCCH scheduling and Random-access procedure on QoS provided to HTC users when MTC devices coexists with HTC users in the same telecom infrastructure. In fact, the studies mentioned above cannot accurately evaluate performance of a massive number of MTC devices in LTE/LTE-Advanced (LTE-A) networks.

III. MACHINE-TYPE COMMUNICATION IN LTE NETWORKS

MTC is about enabling automated applications that involve device communications over cellular networks [13]. MTC will facilitate the deployment of an infinite number of applications in a wide range of domains, such as transportation, health care, smart energy, supply and provisioning, city automation and manufacturing. Since MTC devices can be easily embedded in different environments (e.g., cars, cell towers and vending machines), they may be deployed in huge quantities connected to the Internet; forming the so-called Internet of Things [9].

The use of LTE networks as the air interface for M2M applications has several advantages. Network coverage of service providers make it possible to deploy MTC devices in most urban and rural areas, and the core network of the LTE system can provide seamless communication between MTC devices and M2M applications. The well established LTE network infrastructure makes it unnecessary to deploy new base stations dedicated to M2M communications.

However, as LTE networks are optimized for H2H traffic, there are several issues on MTC devices accessing cellular networks. Unlike H2H traffic, which is characterized by low frequency and high data-rate, M2M traffic usually feature low data-rate as well as frequent transmissions.

IV. PHYSICAL DOWNLINK CONTROL CHANNEL

The PDCCH carries a message known as Downlink Control Information (DCI), which includes resource assignments and other control information for a UE or groups of UEs. The information fields can be divided into distinct categories as follows: resource allocation information, such as PRBs and assignment duration, transport format information, such as multi-antenna information, modulation scheme and payload size and Hybrid Automatic Repeat Request (HARQ) information, such as process number and redundancy version.

As robustness is the key design criterion of the PDCCH, each DCI message is transmitted using one or more Control Channel Element (CCE). The available aggregation levels are 1, 2, 4 and 8 CCEs and the dynamic aggregation level selection is meant to be performed per user depending on the user channel quality.

The PDCCH needs to be reliable enough to get transmissions through without the need for HARQ, for all cell area. The Block Error Rate (BLER) target for PDCCH is set to 1 %, and to achieve the performance target, both power control and link adaptation are needed. The PDCCH allocation must satisfy certain constraints. The set of PDCCH candidates that a particular UE has to monitor are defined in terms of search spaces and only a single DCI message can be allocated in each CCE. In addition to the UE specific search space, there is a common search space for each aggregation level.

The limited number of the available CCEs on PDCCH and the level of aggregation used by the DCI messages can have a large effect on network performance. This limitation defines how many DCI messages can be transmitted by a given eNB [5]. The PDCCH Manager determines the way in which the DCI messages are allocated on the PDCCH.

The interactions of the PDCCH Manager with uplink packet scheduler, downlink packet scheduler and other entities are shown in Figure 1 [14]. Packet scheduling is implemented in two steps, one in time domain and the other in frequency domain, which significantly reduces the scheduler complexity in frequency domain. The PDCCH resources management is performed between Time-domain (TD) and Frequency-domain (FD) scheduling. The Time-domain Packet Scheduling (TDPS) selects a subset of users for potential allocation for the next Transmission Time Interval (TTI) based on the TD scheduling metric. The TD scheduling metric is typically based on buffering delay to match the strict delay bounds. In this paper, the support of QoS requirements is controlled by the TDPS, leaving the Frequency-domain Packet Scheduling (FDPS) to perform radio channel aware scheduling.

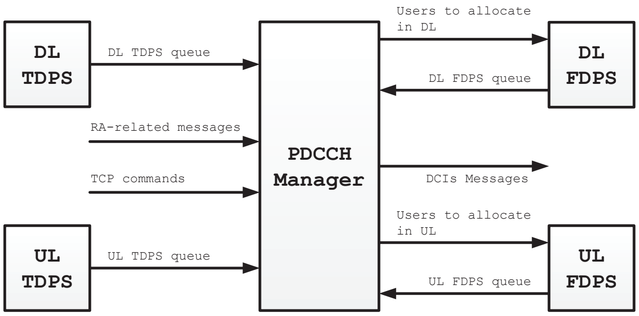


Figure 1. PDCCH Manager architecture [14].

V. PACKET SCHEDULING SCHEMES

Packet scheduling in the two channels (downlink and uplink) is performed separately (one scheduler for the downlink and another one for the uplink direction) at the Medium Access Control (MAC) layer of the eNB. Scheduling is performed at each TTI, when it is decided which PRBs (the smallest unit that the scheduler can allocate to a UE) are allocated to which UE. This decision aims to meet the needs of UE requests, as well as to maximize performance. All the PRBs allocated to a single UE must be continuous with respect to frequency.

A. *Persistent Scheduling*

In persistent scheduling, L1/L2 control signalling is used to allocate a sequence of PRBs as well as a fixed modulation scheme to the UEs at the beginning of active period or inactive period. The allocation should also include resources required for HARQ retransmissions. The persistent allocation can be valid until the UE receives another allocation which will then override the previous one. The major disadvantage of persistent scheduling is the mismatch between resource allocated and resource actually needed.

B. *Dynamic Scheduling*

In dynamic scheduling, the eNB packet scheduler performs scheduling decisions for both downlink and uplink by allocating PRBs to the UEs. As scheduling decisions are made for downlink and uplink in every TTI, new allocations are indicated to the UEs via the PDCCH, indicating which resources are available for transmission/reception of data. Such dynamic mechanism is announced for scheduling high data-rate services enabling resource adaptation flexibility and utilizing time-frequency diversity for better QoS. However, the limitation of this scheme lies in the large control signalling requirement required for every possible transmission. The number of CCEs in the PDCCH actually limits the number of users that can be scheduled in each TTI.

C. *Semi-persistent Scheduling*

The aforementioned problem of PDCCH saturation was noticed in the case of dynamic scheduling scheme for periodical services as Voice-over-IP (VoIP). VoIP is mainly characterized by small packets arriving at regular intervals with tight delay constraints. To handle this situation, semi-persistent scheduling (SPS) was developed in which the eNB scheduler allocates a sequence of PRBs to UEs in time periods previously defined. These resources are used by the UEs to send all its data transmissions using a pre-assigned transport format. If necessary, the scheduler can reallocate different resources or reassign different transport format to enable link adaptation. All the retransmissions are scheduled dynamically using the PDCCH. SPS has proven to be able to support high system capacity in LTE uplink as a consequence of having significantly less control overhead than dynamic scheduling. SPS can guarantee VoIP QoS as well, but it lacks the diversity gains of dynamic scheduling and works only for strictly periodic fixed size packet flow.

VI. PERFORMANCE EVALUATION

Performance evaluation was conducted via simulation using the LTE Simulator (LTE-Sim) [15], which is an event-driven packet level simulator developed in C++ and widely used for simulating LTE/LTE-A networks. We extended the simulator to use a decoupled TD and FD packet scheduler and to support SPS and PDCCH.

The simulation scenarios are composed of a single cell with a 500 meter radius. At the center of the cell, a single eNB with several UE (both HTC users and MTC devices) uniformly located around it. All the UE are created at the beginning of each simulation.

The cell bandwidth adopted is $5\,\text{MHz}$ in the Frequency Division Duplexing mode. The uplink bandwidth is divided into 25 PRBs as specified in the standard [16]. The Packet Uplink Shared Channel (PUSCH) consists of 24 PRBs, used for UE data transmission, with the remaining PRB reserved for the Physical Uplink Control Channel (PUCCH). The PRB used by PUCCH is located at the end of the spectrum to ensure contiguity of available PUSCH resources. The downlink control channels are configured to use the first three Orthogonal Frequency Division Multiplexing (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 [17], 16 CCEs are allocated for this bandwidth. Moreover, since all devices are uniformly distributed in the cell, an aggregation level of 2 CCEs per device is assumed with the same transmission power for all CCEs. The RAP

TABLE I. SIMULATION PARAMETERS

Parameter	Value
System Type	Single Cell
Cell radius	500 m
Channel model	Macro-Cell Urban Model
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
Uplink Scheduler	TD: ZBQoS [7] FD: PF-FME [19]
Max. number of UE passed to the PDCCH Manager	5
PRACH Configuration Index	6
Number of CCE resources	16
Aggregation level for Msg2	8
Aggregation level for Msg4/UL grant/DL assignment	2

algorithm [14] was used to schedule PDCCH resources, which gives high priority to RA-related messages. Since only uplink traffic was evaluated, for every uplink grant message scheduled by the PDCCH scheduler, a downlink assignment is assumed to occur [18].

Both padding and regular Buffer Status Reports (BSRs) are configured to be used in the simulations. When the UEs have data to transmit, they inform the eNB about it through BSR messages. However, if the UE does not have any PUSCH resource allocated for transmission of a BSR, it verifies if valid PUCCH resources are configured to sent a Scheduling Request (SR) message on the PUCCH. The UE can obtain an uplink grant to send the BSR message by sending a SR. If no PUCCH resources are available, then the UE initiates a contention-based Random-access procedure. Since it is not feasible to periodically allocate PUCCH resource simultaneously to several users, whenever a UE needs to send a scheduling request message, a random-access procedure is performed.

HTC users transmit VoIP, video and Constant Bit Rate (CBR) traffic. MTC devices use 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. The first transmission time of MTC devices follows a $Beta(3, 4)$ distribution in a 10 s duration interval.

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, while best effort traffic (modeled as CBR) and MTC traffic use non-GBR bearers. When the delay of a packet is greater than the packet delay bound, the packet is dropped during TTI by the UE at the beginning of uplink transmission. Information about the delay of the Head of the Line packet of each bearer is available in each TTI at the eNB. To avoid intra-user scheduling interference, each UE is assumed to have a single bearer and the traffic of a single class.

Table I shows the configuration parameters used in the simulations.

A. *Impact of the number of MTC devices*

In this subsection, all graphs are presented as a function of the number of MTC devices in the cell. The number of MTC devices was varied from 0 to $2,000$ and the number of VoIP, video and CBR users were fixed to 10, 10 and 5 respectively.

Figure 2(a) and Figure 2(b) show the Packet Loss Ratio (PLR) for the different type of users in the simulation as the number of MTC devices increases. In general, PLR is negatively affected by the growth of the number of MTC devices, with the exception of VoIP traffic with semi-persistent scheduling. As expected, the PLR values of CBR users and MTC devices are higher than those of VoIP and video users. This is because the QoS-aware packet scheduling prioritizes users with strict QoS requirements. When the semi-persistent scheduling scheme is used for VoIP traffic, the PLR values for all traffic types decrease in comparison with the dynamic scheduling because semi-persistent scheduling reduces the utilization of the PDCCH resources, as shown in Figure 2(c).

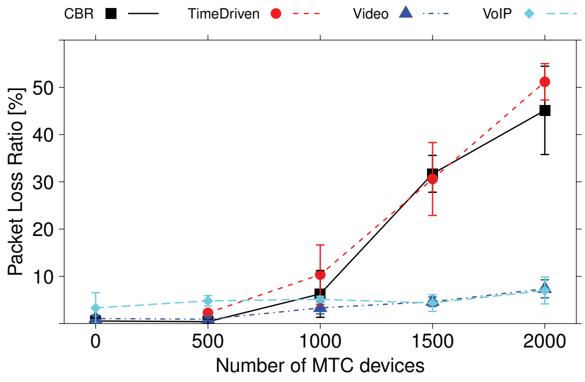
Figure 2(c) shows the increase in CCEs utilization as a function of the increase in the number of MTC devices for both scheduling schemes (dynamic and semi-persistent). This effect shows that the higher the number of MTC devices in the cell, the higher is the number of UE in the eNB that must be signaled on the PDCCH. When the semi-persistent scheduling scheme is used, the utilization of the CCEs is lower than when the dynamic scheduling scheme is used, because the VoIP users do not need to be signalled by the eNB on the PDCCH when they are scheduled. As the VoIP users do not need to be signaled on the PDCCH, other UE can be scheduled, thus increasing the average number of users scheduled per TTI, as shown in Figure 2(d). As a result, the PLR of other types of traffic (Figure 2(a) and 2(b)) is also reduced.

B. *Impact of the number of VoIP users*

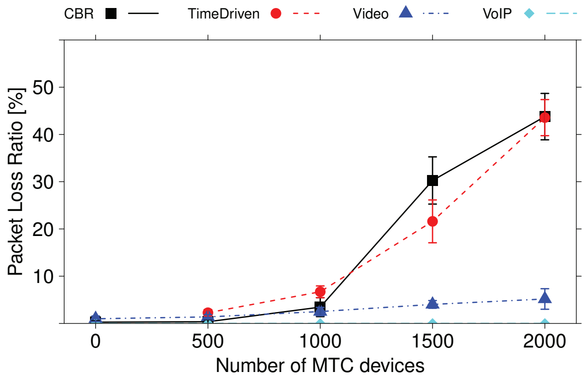
This subsection evaluates the impact of VoIP users on the performance of different scheduling paradigms. All graphics are presented as a function of the number of VoIP users in the cell for different types of users in the simulation. The number of VoIP users was varied from 0 to 160 and the number of video users, CBR users and MTC devices were fixed to 10, 5 and 500 respectively.

Figure 3(a) and Figure 3(b) show the PLR for dynamic and semi-persistent scheduling, respectively. The PLR is negatively affected when dynamic scheduling is used, as shown in Figure 3(a). With this type of scheduling, the PLR sharply increases after 40 VoIP users for CBR users and MTC devices (both transmitting non real-time traffic). The PLR of video and VoIP users (real-time traffic) slowly increases as the number of VoIP users increases up till 80 VoIP users in the cell, after that, the PLR values increase at a faster rate, reaching roughly 20% with 160 VoIP users in the cell. This value of PLR is actually high for video and voice services, degrading the QoS provisioning to users using those services.

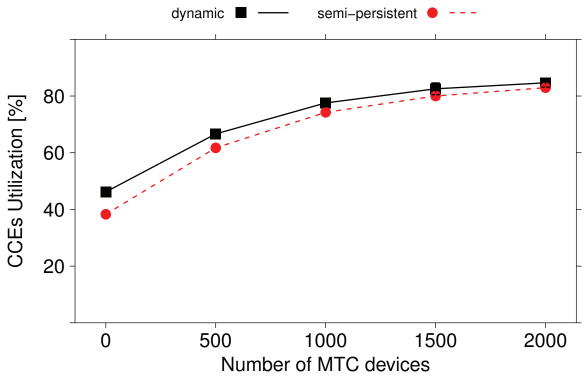
Such increase in packet loss is mainly a consequence of PDCCH saturation (Figure 3(c)). The CCE utilization reaches saturation (80%) with 40 VoIP users, when the PLR of real-time traffic starts to increase (Figure 3(a)). Signalling on the PDCCH involved in the dynamic scheduling resource increases



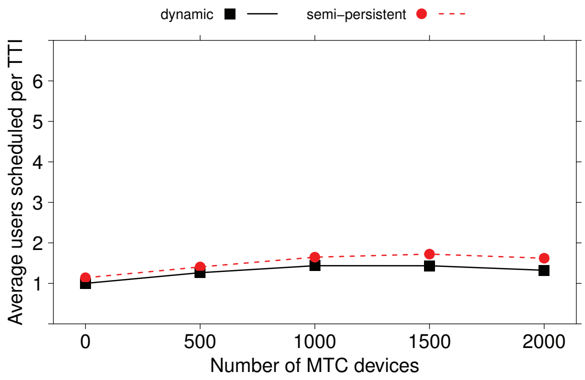
(a) Packet loss ratio - Dynamic scheduling



(b) Packet loss ratio - Semi-persistent scheduling

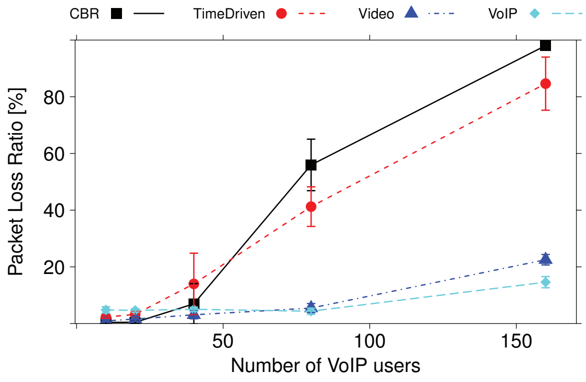


(c) CCEs utilization

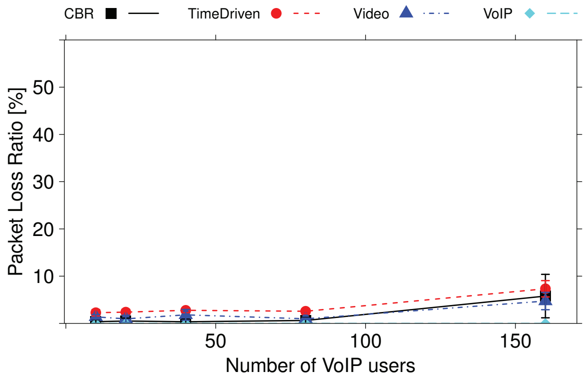


(d) Average number of users scheduled per TTI

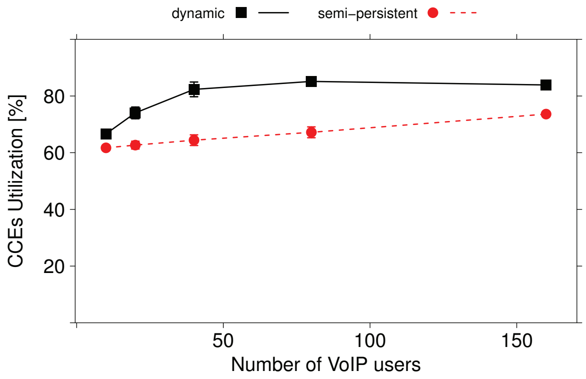
Figure 2. Effect of the number of active MTC devices on performance metrics.



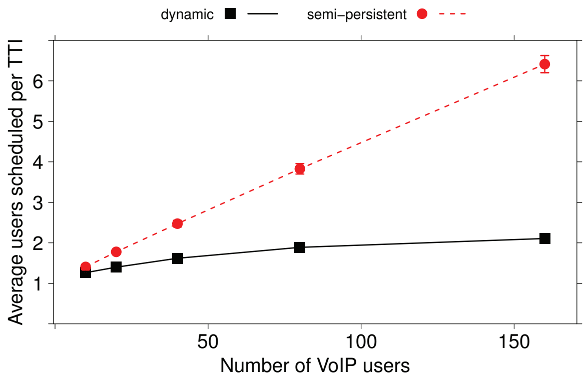
(a) Packet loss ratio - Dynamic scheduling



(b) Packet loss ratio - Semi-persistent scheduling



(c) CCEs utilization



(d) Average number of users scheduled per TTI

Figure 3. Effect of the number of active VoIP users on performance metrics in scenarios with 500 MTC devices.

as the number of VoIP users increases since every time a VoIP user has a packet to transmit it consumes control resources to obtain uplink resources. As the number of PDCCH resources available is limited, the increment in the number of VoIP users leads to saturation of the PDCCH.

This effect can be better understood when the average number of users scheduled per TTI is considered (Figure 3(d)). The use of the semi-persistent scheduling for VoIP users causes an increase in the average number of users scheduled per TTI as the number of VoIP users increase. This can be easily explained by the fact that VoIP users are previously scheduled by eNB, which removes the need of disputing control resources with other users to be scheduled. This increases the number of users per TTI and decreases the CCEs utilization, as shown in Figure 3(c).

The PLR values of CBR, video and M2M traffic slightly increase as the number of VoIP users is higher than 80 VoIP users, when the semi-persistent scheduling is used (Figure 3(b)). This happens because VoIP users require reservation of periodic PRBs when using semi-persistent scheduling, which affects the flexibility of scheduling and the amount of PRBs available for the other types of traffic.

VII. CONCLUSION

In this paper, it was evaluated the impact of massive number of MTC devices on traditional HTC users in LTE network when using both dynamic and semi-persistent scheduling. Results showed that MTC edvices negatively affects the performance of HTC users in LTE networks, specially real-time users (VoIP and video applications), which have strict delay requirements. This occurs due to several factors, such as: limitation on the PDCCH resources, the need to perform RA procedure to send the SR and packet scheduling not being design to M2M traffic. The issue of excessive control overhead associated with dynamic scheduling scheme has been widely discussed as a roadblock for MTC over LTE. Although the semi-persistent allocation scheme currently in practice for VoIP offers a solution with less control signalling, it does not provide flexibility in allocation of radio resources.

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