Uplink Scheduling for Smart Metering and Real-Time Traffic Coexistence in LTE Networks

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***Abstract*—Smart Grid (SG) is considered as the future of the electrical power distribution system, where Advanced Metering Infrastructure (AMI) will let utilities to acquire and analyze the consumption data and access and control several home appliances for power balancing purposes through special devices, known as Smart Meters (SMs). Long Term Evolution (LTE) appears as a promising solution to handle the SMs traffic due to its high bandwidth and flexibility. However, given that SMs need to periodically send measurements to the eNodeB (eNB), the network uplink could be a potential bottleneck, thus affecting the users running real-time applications, such as voice calls. To overcome this problem, in this paper, we present a scheduling policy that jointly considers the channel quality, the traffic prioritization and the AMI Packet Delay Budget (PDB) in order to provide the SMs with the required resources and reduce the impact on the real-time traffic. Extensive simulation experiments have been carried out, indicating the smooth coexistence between the SMs and the voice users, since the proposed scheduler achieves higher percentage of served users compared to widely employed schedulers.**

I. Introduction

The Smart Grid (SG) concept has been recently introduced to promote a new era of electricity generation, transmission, distribution and consumption. In particular, the SG applications focus on reliability, flexibility and environmental concerns in order to improve the quality of life of the energy consumers and enable the electric utilities to gain higher level of control over the energy management. Advanced Metering Infrastructure (AMI) allows utilities to collect, measure and analyze energy consumption data for grid management, outage notification and billing purposes. Moreover, through AMI, utilities have access and control to different home appliances (including thermostats, air conditions, washing machines and dryers, among others) in order to properly schedule their activity period to balance the power generation and demand in the grid, thus avoiding power peak loads that potentially lead to powert blackouts. In the context of AMI, Smart Meters (SMs) play a key role to the connection between the utility and the end-users, by recording the electric energy consumption in particular time intervals. The data transferred from SMs to the provider mainly consist of the electricity use of the home devices. This data rate may vary from 10 kb/s in case of a typical home, while it can scale up to 100 kb/s in bigger installations, such as huge buildings and office facilities [1].

Taking into account the peculiarities of SG networks and the fact that many devices need to periodically send information to a central controller, the uplink transmission could constitute a severe bottleneck for the communication, requiring advanced protocols and standards. Recently, Long Term Evolution (LTE) has been introduced by the 3rd Generation Partnership Project (3GPP), offering high data rates, efficient use of the radio resources and support for service differentiation for applications with different Quality of Service (QoS) requirements. Hence, LTE appears as a promising solution, able to handle the massive communication of the SMs. However, LTE commercial networks typically serve several end-users with various bandwidth-demanding real-time applications (e.g., voice, video, gaming, etc.) and, consequently, the smooth coexistence of these users along with the periodic smart metering traffic becomes of great importance [2].

The aforementioned issue has been recently studied in [3], [4]. More specifically, in [3], the authors examine an LTE network, consisting of SMs and User Equipment terminals (UEs), where all the SMs transmit simultaneously due to a fault or outage detection on the power network. The authors adopt a channel dependent scheduler and consider two different architectures for the connection of SMs to the eNodeB (eNB), i.e., direct and via relays. In the former case, they introduce a random delay on the transmission of the SMs in order to reduce the network congestion, while, in the latter, they exploit the delay of the connection between SMs and the relays. In [4], the authors study a similar scenario (with UEs and SMs) and they develop an admission control algorithm, where a fixed amount of resources is reserved for a SM, when it is polled by the Round Robin scheduler. Therefore, in case of congestion, the resource reservation may provoke significant degradation to the real time applications running in the UEs.

In this paper, we present a novel LTE uplink scheduling strategy that facilitates the smooth coexistence between SMs and typical UEs in the network. The proposed scheduler jointly considers: i) the service differentiation, ii) the particular delay constraints of the SMs, and iii) the channel quality, in order to guarantee the proper SG communication, without compromising the QoS of the existing real-time sessions in the network. In addition, taking into account that the high number of direct connections to the eNB implies increased control information, we exploit the benefits of cooperative communication by enabling a set of relays to provide the link between eNB and SMs.

The remainder of this paper is organized as follows. A brief description about the different types of schedulers is provided in Section II. In Section III, we describe the system model. In Section IV, we introduce the uplink scheduling mechanism. In Section V, we evaluate the performance of the proposed scheduler and we discuss the simulation results. Finally, Section VI concludes the paper.

II. Background and Related Work

The LTE employs Orthogonal Frequency Division Multiplexing Access (OFDMA) and Single Carrier Frequency Division Multiple Access (SC-FDMA) in downlink and uplink, respectively. The reason for the selection of SC-FDMA in the uplink consists in its inherent advantage to reduce the power consumption of the UEs, since it provides a low Peak-to-Average Power Ratio (PAPR) for the transmit waveform compared to an OFDMA transmission [5]. The LTE standard supports a QoS classification for the applications running in the UEs, providing a QoS-based prioritization of the users. More specifically, each service is associated with one QoS Class Identifier (QCI), which specifies the quality requirements for a given class, such as the priority and the Packet Delay Budget (PDB) [6] that defines an upper bound for the time that a packet may be delayed between the UE and the core network. Uplink scheduling in LTE was mainly introduced to improve important performance metrics such as delay and throughput. Besides, LTE uplink scheduling should satisfy the constraint that all the Resource Blocks (RBs) assigned to a service request must be contiguous in frequency domain, due to the nature of the LTE uplink multiple access scheme (SC-FDMA) [7].

The network throughput maximization and the fair resource allocation among users is a fundamental trade-off that the uplink schedulers should handle. Round Robin is the scheduling mechanism that focuses mainly on fairness. This technique foresees an equal distribution of resources among users, i.e., the users are served in a sequential manner, receiving the same amount of resources without taking into account the channel conditions and the QoS priority requirements. On the other hand, the work in [8] has showed that throughput maximization can be achieved by exploiting the multiuser diversity. In a pure opportunistic approach, the scheduler will assign the resources giving priority to the user with the best channel conditions but, in this way, users with poor channel quality may be never scheduled. This approach is known as MaxRate scheduling in the literature.

With regard to the LTE particularly, several schedulers have been proposed in the literature [3], [4], [9]–[11]. In [9], the authors present a channel dependent scheduling algorithm, without considering the contiguity in frequency resource allocation in LTE uplink. In [10], the authors develop a scheduling strategy that is a combination between Round Robin and MaxRate. Their main objective is to balance the LTE network throughput and the fairness among the different users. In [11], the authors present an LTE uplink scheduling procedure that takes care of QCIs of the different users. They consider nine QCI classes and they show that a multi-channel scheduling algorithm (MC-SA) has better performance than the single-channel scheduling algorithm (SC-SA) in terms of throughput. However, although MC-SA succeeds to serve requests with higher throughput requirements, it significantly reduces the throughput of the other services (voice, web) compared to a SC-SA system that only assigns one RB per Transmission Time Interval (TTI) to a given request. In [3], the authors examine whether the public LTE network is suitable for SG automatic metering usage in a worst case scenario, i.e., when all the SMs need to transmit data due to fault detection. They investigate two different cases: i) all the SMs are directly connected to the eNB, and ii) the SMs are connected using the IEEE 802.15.4 standard to traffic aggregators (relays). They adopt a channel dependent scheduler and, in the first case, they assign a random delay of [0, 1) seconds to the SMs data transmission, while, in the second case, they exploit the inherent delay generated by the IEEE 802.15.4 link between the SMs and the cluster head. In [4], the authors consider the uplink segment of an LTE network with SMs and UEs and develop an admission control algorithm that reserves two RBs for each SM. They adopt the Round Robin scheduler to poll all the devices and, in case of congested eNB, the RBs required by SMs may be reserved from the connected UEs, despite the fact that they could execute real-time applications.

III. System Model

The system, depicted in Fig. 1, consists of an LTE base station (eNB), a set of N UEs and a set of M relays uniformly distributed and directly connected to the eNB. Each relay provides the link to the eNB to a set of L_C SMs and, hence, the total number of SMs in the network is $L_T = L_C \cdot M$. The employment of relays offers a great benefit to the communication, as it reduces the total number of direct connections and guarantees a more efficient usage of the RBs. In particular, in LTE, the minimum amount of resources that can be assigned to a device is one RB [7]. Consequently, in case of low data rates (e.g., SMs), there could be a waste of radio resources, since the symbols carried by a RB may be not fully utilized, but we can overcome this issue by aggregating the SMs data streams to a relay.

For all the direct connections, i.e., UEs and relays, the communication link with the eNB is affected by path loss, which is modeled as COST231 Hata urban propagation model [12]:

$$\begin{aligned} PL[dB] = {} & (44.9 - 6.55\log_{10}(h_{bs}))\log_{10}(\frac{d}{1000}) \\ & +45.5 + (35.46 - 1.1h_{ms})\log_{10} f_c \\ & -13.82\log_{10}(h_{bs}) + 0.7h_{ms} + C, \end{aligned} \tag{1}$$

where h_{bs} is the eNB antenna height, h_{ms} is the UE antenna height, f_c is the carrier frequency, d is the distance between eNB and the UE[1], and C is a constant factor, equal to 0 dB for suburban macrocell environments.

LTE standard provides different levels of QoS to the users, depending on the kind of service that is running on their device. Accordingly, we have adopted three ($i = 3$) classes of users with different QoS requirements. The first regards the SMs, while the second and the third class regard conversational voice (which is a real-time service) and video applications, respectively. For each service class QCI_i, we consider a guaranteed bit rate, denoted by GBR_i. The communication between the SMs and the eNB takes place in two phases. In the first phase, the SMs send their data stream to the respective

[1]The distance d may vary between 30 and 700 meters according to the device heights and the topology presented in Fig. 1.

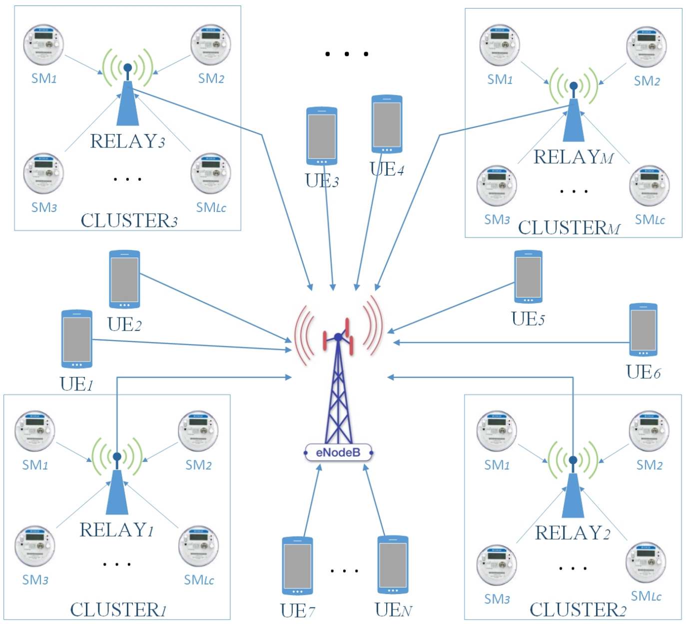

Fig. 1: System Model

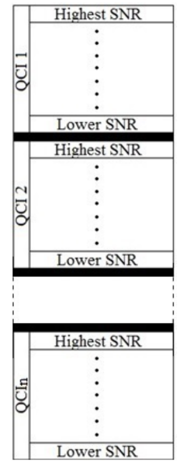

Fig. 2: Scheduler's buffer

relay in each cluster. In the second phase, the relay transmits the aggregated data stream to the eNB. Our study is focused on the second phase of the transmission, assuming that the relays have collected the SM data in their buffers and they are ready to transmit.[2] Taking into account this realistic system model, in the following section, we introduce the proposed scheduler that guarantees the smooth coexistence of SMs and real-time traffic applications in LTE networks.

IV. QoS-aware Max Rate (MR-QoS) Uplink Scheduler

Let us recall that, in the considered system model, all the transmitting devices are located at a random distance from the eNB and, since the channel is affected by path loss, users experience different channel conditions and they consequently have different Signal-to-Noise Ratio (SNR). In the link adaptation process, the SNR of each user determines a specific modulation and coding scheme, which denotes the amount of bits carried per symbol. Therefore, as all connections have GBR traffic, the number of RBs that each user requires can be computed. After this procedure, all the required information is available to the scheduler in order to initiate the resource allocation by creating the scheduling buffer. In particular, this buffer is generated in two phases: in the first phase, the users are classified in ascending order according to their QCI. In the second phase, every group of users that belongs to the same QCI class is sorted in ascending order with respect to the channel quality. A graphical display of the scheduling buffer, as generated at the end of two phases, is shown in Fig. 2.

In order to increase the resource allocation efficiency of MR-QoS scheduler, we exploit the acceptable delay (PDB) for the transmission of the packet to the core network. More specifically, since the QCI_1 class, which refers to relays, has a higher PDB [1], [14], [15] than the other two classes [6], we introduce the concept of Adaptive Delay (AD) that corresponds to the time that the scheduler may delay the RBs assignation to QCI_1 class. Employing the AD, we ensure that all the relays (and consequently the SMs) are able to transmit respecting their delay constraints. The AD may be computed as:

$$AD = \frac{PDB}{TTI_{num}}, \tag{2}$$

where PDB denotes the acceptable delay and TTI_{num} refers to the number of TTI needed by the relays to transmit the SMs data respecting their PDB, calculated as:

$$TTI_{num} = \frac{RB_{Total}}{RBperTTI}, \tag{3}$$

where RB_{Total} is the number of RBs required by all the relays in the network, while $RBperTTI$ corresponds to the number of RBs available in each TTI[3].

A detailed flowchart with the scheduling operation is illustrated in Fig. 3. As depicted in the figure, once the buffer is created, the scheduler assigns all the RBs demanded by each user, starting from the top of the buffer. During this process, the following operations are performed. First, the scheduler examines whether the current TTI is a multiple of AD. In this case, it assigns RBs to relays until the end of the TTI, otherwise it allocates the resources to other users inside the buffer. When a scheduled device receives all the RBs required, the scheduler checks the resource availability in the current TTI. In case there are remaining resources, it assigns the RBs to the next user in the buffer. When the RBs of a particular TTI have been exhausted and a user still needs resources, the scheduler memorizes the status of this user and provides the required resources in the next TTI. Therefore, following the priority buffer, all users are served.

[2]During the first phase of the transmission, opportunistic routing schemes can be also employed to improve the multi-hop communication between the SMs and the relays [13].

[3]According to the LTE standard, in every TTI (whose duration is 1 ms), the scheduler has available a fixed amount of RBs to distribute among the connected users, depending on the system's bandwidth.

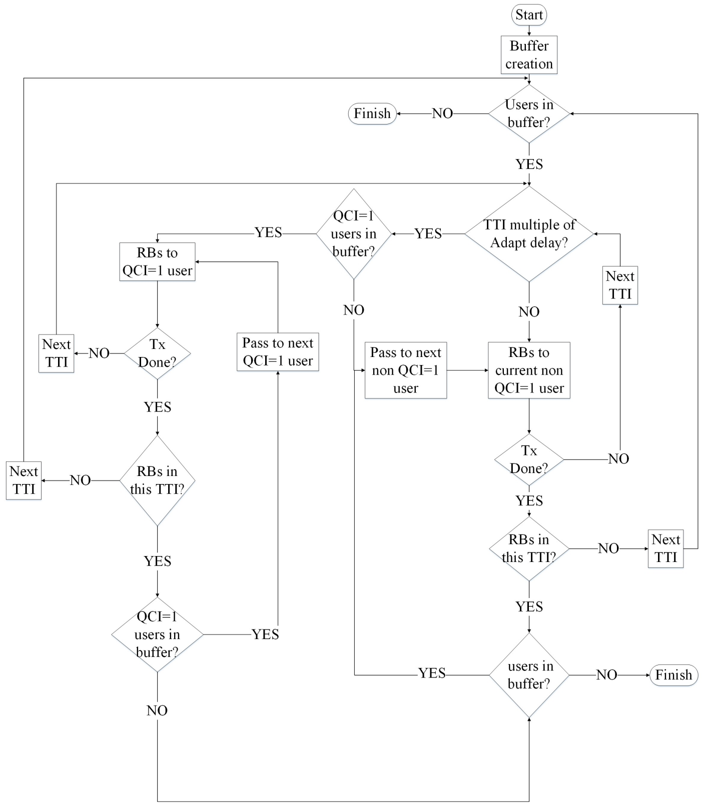

Fig. 3: Scheduler's operation flow chart

A. MR-QoS Operational Example

A simplified example of the MR-QoS RBs assignation policy is provided in Fig. 4. In this example, we consider ten available RBs per TTI, i.e., $RBperTTI = 10$, and three different user categories ($QCI_1 - QCI_3$), whose parameters are presented in Table I. In addition, we assume a delay budget equal to $PDB = 6$ ms, which results in $AD = 3$ ms by taking into account Eq. (2) and (3).

Therefore, in this particular example, the scheduler operates as follows: first, it allocates the resources to QCI_1 users until the end of TTI_0. At this point, the scheduler examines whether the next TTI (i.e., TTI_1) is a multiple of the computed AD. As this is not the case, the scheduler initiates the RBs assignment to QCI_2 users, thus following the buffer's order. As we can see in Fig. 4, in the current TTI, there are not enough available resources to allow the transmission of user 13, since the user requires 4 RBs, but there are only 2 RBs available. In this case, the scheduler memorizes the status of this user, resuming the RBs allocation in the next TTI non multiple of AD. Since neither the next TTI (TTI_2) is a multiple of AD, the scheduler will continue the resources allocation for user 13. Once all the QCI_2 users perform their transmissions, the scheduler checks if there are still available resources in the current TTI and, as showed in Fig. 4, it starts assigning RBs to QCI_3 users, particularly to user 15. Again, the resources available in this TTI (TTI_2) are exhausted and the scheduler passes to the next TTI, memorizing the status of the current user (ID=15). However, in this case, TTI_3 is a multiple of AD and, as a result, the scheduler continues the resource allocation to QCI_1 users. At the beginning of TTI_4, the allocation of user 15 is resumed. Following the buffer, the scheduler will perform the resources allocation for all the users.

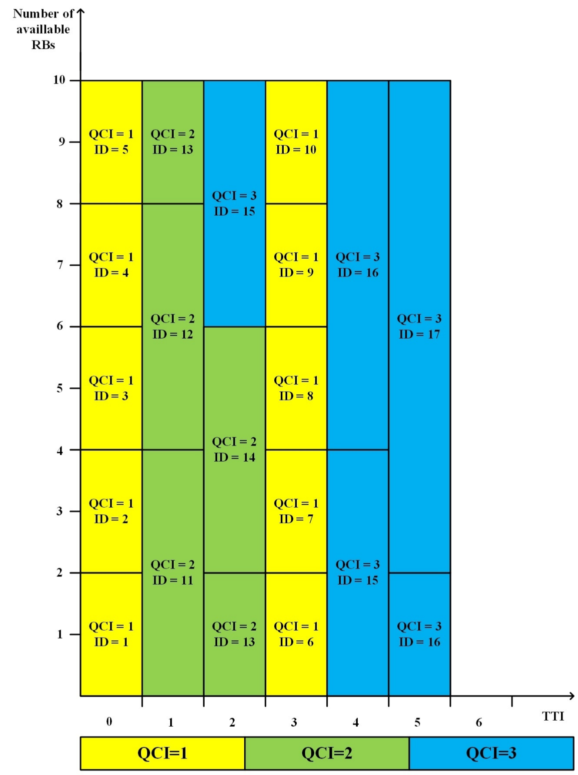

Fig. 4: MR-QoS Scheduling Operational Example

TABLE I:
Example Parameters

QCI	Number of Users	Device ID	RBs per TTI
1	10	1 - 10	2
2	4	11 - 14	4
3	3	15 - 17	8

V. Performance Evaluation

We have developed a time driven C++ tool that simulates the scheduler's operation, considering the uplink characteristics of the LTE network. In this section, we present the simulation parameters, the methodology for the experiments and the simulation results.

A. Simulation Parameters and Methodology

In our experiments, we assume a fixed number of clusters ($M = 5$) with $L_C = 10$ SMs connected to each cluster head (relay), thus having $L_T = 50$ SMs in total. In addition, we consider four different cases for the number of UEs, i.e., $N \in \{10, 20, 30, 40\}$. Regarding the traffic prioritization, the network connections are classified into three ($i = 3$) classes with respect to their different QCIs. In particular, all the relays belong to QCI_1, while the UEs are equally divided into real-time voice (QCI_2) and video (QCI_3) users. The particular traffic parameters[4] for each class are defined in Table II, while the LTE simulation parameters are listed in Table III.

For the evaluation of the proposed scheduler, we have also implemented two benchmark policies, i.e., the Round Robin (RR) and the Max Rate (MR) scheduling. For the comparison of the three schemes we have adopted the served user percentage metric, defined as:

$$Served\ Users(\%) = \frac{Number\ of\ Served\ Users\ in\ QCI_i}{Total\ Number\ of\ Users\ in\ QCI_i}, \quad (4)$$

which is an indicator of the portion of users that are served without violating their delay constraints.

TABLE II:
Users Traffic Parameters

User Type	QoS Class ID	GBR	PDB
Smart Meters	QCI_1	56 kb/s	1980 ms
UE Voice	QCI_2	30 kb/s	80 ms
UE Video	QCI_3	128 kb/s	130 ms

TABLE III:
LTE Parameters

LTE Parameters	
Bandwidth	10 MHz
Resource Blocks per TTI	50
Resource Block bandwidth	180 kHz
Carrier frequency	1800 MHz
Transmission Power	23.01 dBm (UEs) - 30 dBm (Relays)
Height	1.5 m (UEs) - 3 m (Relays)
Modulations	QPSK, 16-QAM, 64-QAM (Relays)
Noise power spectral density	-174 dBm/Hz
Path loss	COST231 Hata urban propagation model
Scheduling mode	MR-QoS, Round Robin, MaxRate

B. Simulation Results

Fig. 5 demonstrates the percentage of served relays in QCI_1 for the three different scheduling policies and various number of total users in the network (i.e., 60-90). As it can be observed, the proposed MR-QoS scheduler succeeds in serving the SM traffic in all cases, independently of the total number of users in the system. In addition, MR-QoS outperforms the other two schedulers in most scenarios, while the difference increases with the number of users. More specifically, in the particular case of 90 users in the network, MR-QoS serves 19% and 81% more QCI_1 users compared to MR and RR, respectively.

Regarding the real-time traffic, Fig. 6 compares the performance of the three schedulers in terms of the percentage of QCI_2 users that meet their PDB constraints. As we can see, our proposed scheduling policy guarantees the service of all voice users and the smooth coexistence with the SMs, even in extreme cases with high traffic in the network. By

[4]The PDB and the data rate for the LTE users can be found in [6] and [16], while the SM characteristics can be found in [15] and [17]. However, in our case, a value of 20 ms has been subtracted from all values in order to take into account the average delay between the radio base station and the core network.

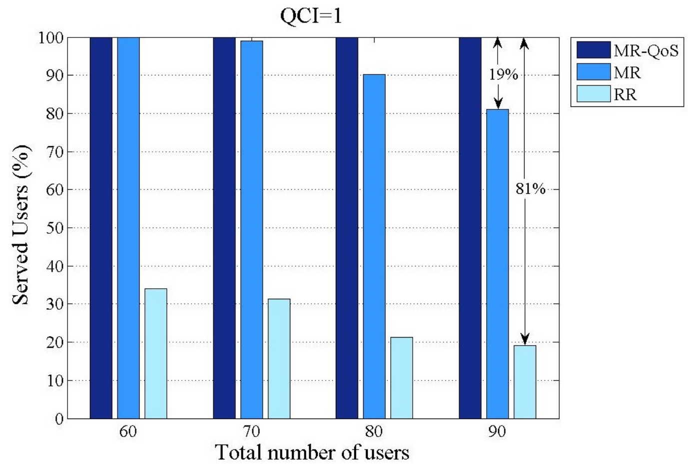

Fig. 5: Served QCI_1 users under different scheduling policies

jointly considering the QoS, the channel conditions and the PDB of the SMs, MR-QoS schedules the SG traffic in a way such that to respect the resource demands of the real-time traffic UEs. Similar to the QCI_1 case, as the total traffic increases, the difference between the proposed scheduler and the other two solution is also increasing, reaching 12% and 20% (compared to MR and RR, respectively) in case of 90 total network users. It is worth noting that this service guarantee is of great importance for mobile network operators, since the voice service is highly prioritized with respect to other applications.

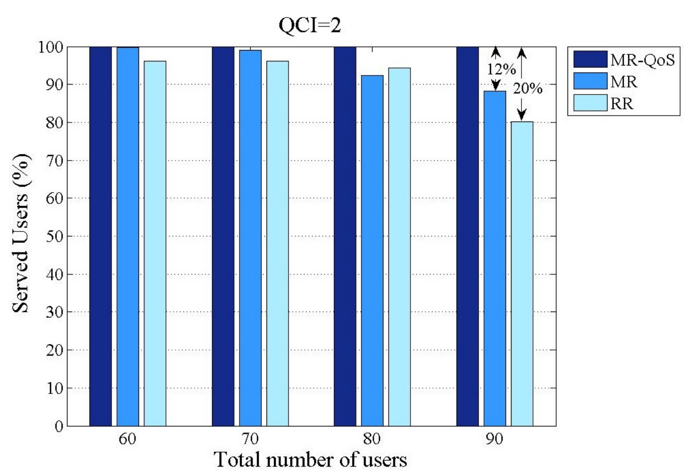

Fig. 6: Served QCI_2 users under different scheduling policies

The simulation results with regard to the QCI_3 (i.e., video applications) are plotted in Fig. 7. In this case, the proposed MR-QoS outperforms RR in all the different scenarios, while it achieves a slightly lower user service compared to MR. More specifically, the maximum gain of MR is estimated as 16% for 90 total users in the network. However, let us recall that this loss is compensated by the MR-QoS performance for QCI_1 and QCI_2 in the same scenario, where the gain is even higher and concerns more critical applications. Finally, the inefficiency of the RR algorithm is clearly shown in all cases.

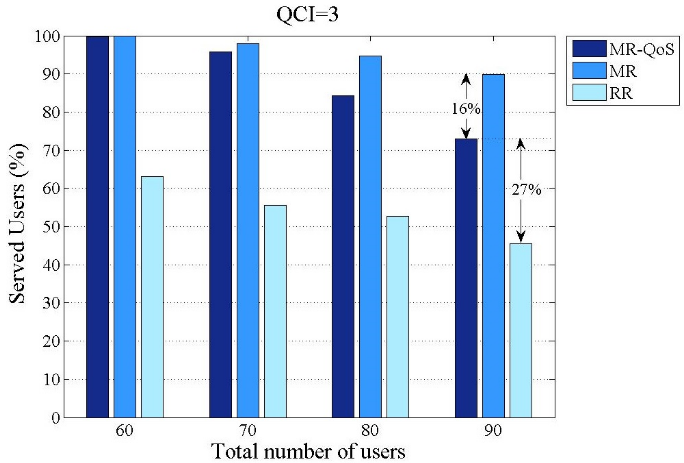

Fig. 7: Served QCI_3 users under different scheduling policies

VI. Conclusion

In this paper, we introduced a novel uplink scheduling strategy for LTE networks in order to guarantee the smooth coexistence between SMs and UEs with real-time applications (e.g., voice). The proposed policy (namely MR-QoS) jointly considers the service differentiation, the channel conditions and the delay constraints during the uplink scheduling. Extensive simulation results have been carried out, proving the efficiency of MR-QoS and its ability to guarantee 100% service of the SMs and the voice users. In addition, it was shown that the proposed scheduler outperforms traditional scheduling mechanisms (i.e., Round Robin and Max Rate) up to 81% with regard to SM traffic. In our future work, we are planning to provide an analytical validation for the proposed scheduling and exploit new transmission techniques (e.g., network coding) to further enhance the system performance.

Acknowledgements

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