

LTE Performance Evaluation Based on two Scheduling Models

LTE downlink and uplink analysis

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Abstract—This paper presents a detailed analysis on the Long Term Evolution performance in both downlink and uplink directions emphasizing the most important aspects that influence the performance indicators. Round Robin and Weighted Round Robin scheduling strategies, in time domain and time-frequency domain, are used in different scenarios concerning antenna configuration, number of users and types of services in order to evaluate cell throughput, average user throughput and cell capacity. The control channels bring some limitations in the number of users served and on the actual transmission bandwidth when time-frequency domain packet scheduling is implemented and all these are reflected in the simulation results. This paper offers an image of the LTE network performance in various scenarios, the most important aspect being the cell capacity evaluation with a certain minimum or expected service throughput.

Keywords – LTE; OFDMA; SC-FDMA; scheduling; control channel; Round Robin.

I. INTRODUCTION

In the context of a continuous mobile traffic growth along with the high requirements of users and operators, 3GPP (3rd Generation Partnership Project) has standardized a new technology called Long Term Evolution (LTE) as the next step of the current 3G/HSPA (High Speed Packet Access) networks to meet the needs of future broadband cellular communications. It may be considered as a milestone towards 4G (Fourth Generation) standardization. The requirements set for LTE that are specified in [1] envisage high peak data rates, low latency, increased spectral efficiency, scalable bandwidth, optimized performance for mobile speed, etc. In order to fulfill this extensive range of requirements several key technologies have been considered for LTE radio interface of which the most important are: multiple-access through Orthogonal Frequency Division Multiple Access (OFDMA) in downlink and Single Carrier - Frequency Division Multiple Access (SC-FDMA) in uplink and multiple-antenna technology.

Packet Scheduling is one of LTE Radio Resource Management (RRM) functions, responsible for allocating resources to the users and, when making the scheduling decisions, it may take into account the channel quality information from the user terminals (UE), the QoS (Quality

of service) requirements, the buffer status, the interference situation, etc. [2]. Like in HSPA or WiMAX, the scheduling algorithm used is not specified in the standard and it is eNodeB (Evolved NodeB) vendor specific.

The LTE downlink has been previously analyzed in several papers like [3], [4], [5] and [6]. The authors evaluated the system and/or user throughput and the fairness of the scheduling algorithms used in their simulations, but the work was restricted either to SISO (Single Input Single Output) antenna technology, or the users experiencing the same radio conditions. Very few papers considered the PDCCH (Physical Downlink Control Channel) limitation in the number of users served and the terminal category impact. For LTE uplink there are fewer papers, some examples being [7], [8] and [9]. As for downlink, the control channels limitation is scarcely mentioned and evaluated and none of them analyzes the priority set for a specific type of users and its impact on cell capacity and throughput.

In this paper, we evaluate the performance of packet scheduling in downlink and uplink LTE using the Round Robin and Weighted Round Robin strategies through the results obtained for the average cell throughput, the achieved user throughput and the system capacity. These results may be considered in the LTE network design, in order to approximate the number of users that can be served with a certain throughput in a commercial LTE network.

The remainder of this paper is organized as follows. Section II discusses several aspects on scheduling and assigned resources in downlink LTE system followed by an insight on resource allocation in LTE uplink presented in Section III. Section IV describes the Round Robin and Weighted Round Robin scheduling models used in the simulations and Section V depicts the results of the simulated scenarios. The conclusions are driven in Section VI.

II. SEVERAL ASPECTS ON RESOURCE ALLOCATION IN LTE DOWNLINK

The LTE downlink is mainly characterized by OFDMA as multiple access scheme and MIMO (Multiple Input Multiple Output) technology. The benefit of deploying OFDMA technology on downlink LTE is the ability of allocating capacity on both time and frequency, allowing

multiple users to be scheduled at a time. The minimum resource that can be assigned to a user consists of two Physical Resource Blocks (PRBs) and it is known as chunk or simply Resource Block (RB) [2],[10]. In downlink LTE one PRB is mapped on 12 subcarriers (180 kHz) and 7 OFDM symbols (0.5 ms) and this is true for non-MBSFN (Multimedia Broadcast multicast service Single Frequency Network) LTE systems and for normal CP (Cyclic Prefix). Scheduling decisions can be made each TTI (Time Transmission Interval) that in LTE is equal to 1 ms.

For non-real time services dynamic scheduling is usually used as it provides flexible and even full utilization of the resource. This scheduler performs scheduling decisions every TTI by allocating RBs to the users, as well as transmission parameters including modulation and coding scheme. The latter is referred to as link adaptation. The allocated RBs and the selected modulation and coding scheme are signaled to the scheduled users on the PDCCH (Physical Downlink Control Channel). The dynamic packet scheduler also interacts closely with the HARQ (Hybrid Automatic Repeat Request) manager as it is responsible for scheduling retransmissions and it may also take into account the QoS attributes and buffer information [6], [11].

The schedulers in the eNodeB may or may not take into consideration the channel information when making scheduling decisions. An alternative to channel-dependent scheduling is Round Robin strategy that serves the users in cyclic order, regardless the channel information.

Although OFDMA technology allows the users to be multiplexed in time and frequency, the scheduler, according to the implemented algorithm, may choose to allocate the entire bandwidth to a single user, reducing the scheduling to be done only in time domain. The channel-sensitive scheduling done in time domain only is called Non-Frequency Selective Scheduling (NFSS) and the scheduling exploiting the channel variations in both time and frequency is known as Frequency Selective Scheduling (FSS) as specified in [12]. Fig. 1 illustrates an example of FSS for two users [6], [13].

When scheduling is done in time and frequency domain, independently if it is channel-aware or not, the number of multiplexed users in each TTI is limited by the number of

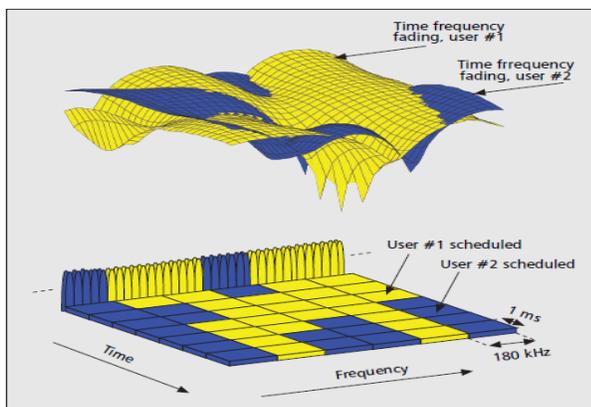


Figure 1. Frequency selective scheduling illustration for two users in downlink LTE

PDCCHs that can be configured. This depends on the system bandwidth, the number of symbols signaled for PDCCH allocation, the PDCCH format number, etc. [10], [11], [14], [15].

The PDCCHs are intended to provide both uplink and downlink scheduling information and in the assumption of half of the users making downlink transmissions, the maximum number of scheduled users per TTI in downlink LTE is half of the number of PDCCHs available. The authors from [11] discussed this constraint and proposed a three-step packet scheduling algorithm as it is depicted in Fig. 2 [11].

The highest number of PDCCHs is obtained with PDCCH format 0 (excellent radio conditions), but in real scenarios there will be a mix of PDCCH formats in order to realize link adaptation [11].

From all the multiple antenna techniques that can be used in downlink LTE the most performance improvements in terms of cell/user throughput and cell capacity are reached with MIMO (Multiple Input Multiple Output). The baseline antenna configuration for MIMO and antenna diversity is two transmit antennas at the cell site and two antennas at the terminal. The higher-order downlink MIMO and antenna diversity (four TX and two or four RX antennas) is also supported. The basic MIMO schemes applicable to the downlink are illustrated in Fig. 3.

These schemes can be applied depending on the scenario (indoor, urban and rural coverage) and the UE capability.

The multi-antenna technology brings a new dimension on mobile radio – SPACE – and its implementation is based on three fundamental principles:

- Diversity gain – Use of the space-diversity provided by the multiple antennas to improve the robustness of the transmission against multipath fading (Fig. 3A).
- Array gain – Concentration of energy in one or more given directions via precoding or beamforming. This also allows multiple users located in different directions to be served simultaneously (so-called multi-user MIMO) (Fig. 3B and Fig. 3D).
- Spatial multiplexing gain – Transmission of multiple signal streams to a single user on multiple spatial layers created by combinations of the available antennas (Fig. 3C) [16].

III. SEVERAL ASPECTS ON RESOURCE ALLOCATION IN LTE UPLINK

The high PAPR (Peak to Average Power Ratio) of the transmitted signal in OFDMA and the limited power of the mobile terminal determined 3GPP to choose a different scheme for LTE uplink – SC-FDMA – in order to optimize the power consumption of mobile handsets.

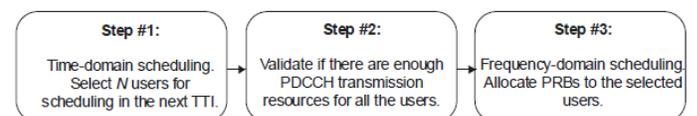


Figure 2. Illustration of a three step scheduling algorithm framework

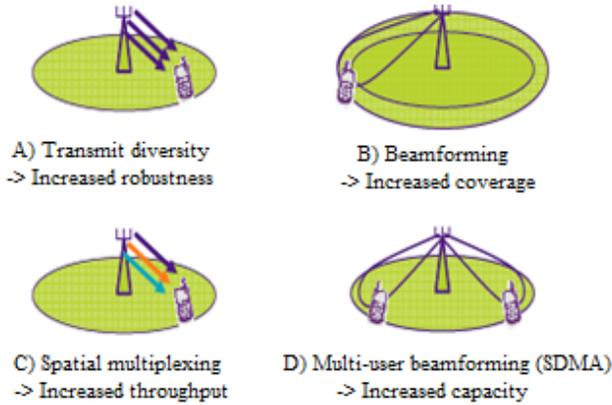


Figure 3. MIMO schemes for LTE downlink

This multiple access technology is a variation of OFDMA, but with initial precoding stage using DFT (Discrete Fourier Transform), which results in each subcarrier carrying a linear combination of data symbols instead of each data symbol being mapped to a separate subcarrier. This results in a single-carrier waveform that exhibits a significantly lower PAPR than OFDMA, but keeps the multipath resistance and the inter-user orthogonality [11].

The smallest resource that can be assigned to a user also consists of two PRBs adjacent in time and for simplicity of expression, in the rest of the paper we will use the term resource block (RB). In uplink LTE one PRB is mapped on 12 subcarriers, each of 15 kHz, and 7 SC-FDMA symbols, with 0.5 ms time duration and this is true for non-MBSFN LTE systems and for normal CP [2], [10]. As well as in downlink, SC-FDMA allows multiple users to be scheduled at a time and the scheduling decisions can be made each TTI.

Unlike OFDMA, SC-FDMA constrains transmission to occur only on adjacent subcarriers in order to maintain its single carrier property. This means that RBs cannot be allocated freely and must be contiguous, limiting both frequency and multi-user diversity.

LTE defines both localized and distributed scheduling in the downlink direction, but only localized scheduling in the uplink direction in order to keep the PAPR small in the SC-FDMA symbols of each user. Fig. 4 compares the localized and the distributed scheduling [17].

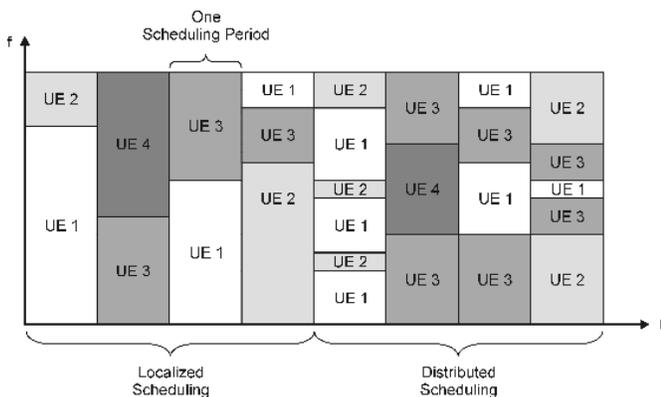


Figure 4. Localized vs. distributed scheduling in LTE

Taking into account that the PDCCH limitation applies also in LTE uplink, the scheduling framework from Fig. 2 can be used in LTE uplink too.

The LTE uplink is more impacted by the control information than the downlink. The actual transmission bandwidth in uplink is limited by the PUCCH (Physical Uplink Control Channel) regions and some typical expected number for different LTE bandwidths are presented in [16] and shown in Table I. PUCCH carries scheduling requests, ACK/NACK information related to downlink data packets, CQI (Channel Quality Information) etc. The number of PUCCH RBs per slot is the same as the number of PUCCH regions per sub-frame.

IV. ROUND ROBIN AND WEIGHTED ROUND ROBIN SCHEDULING MODELS IN LTE

As mentioned in Section II, Round Robin (RR) scheduling is a channel non-aware scheduling scheme that lets users take turns in using the shared resources (time and/or RBs), without taking the instantaneous channel conditions into account. Therefore, it offers great fairness among the users in radio resource assignment, but degrades the system throughput. Weighted Round Robin (WRR) is a variation of RR with priorities defined for different service categories. Time Domain (TD) RR and WRR, as well as Time and Frequency (FD) RR and WRR scheduling models are described in this Section.

A. Time Domain Round Robin and Weighted Round Robin scheduling model

In TD RR the first reached user is served with the whole frequency spectrum for a specific time period (1 TTI), not making use of the information on his channel quality. Then these resources are revoked back and assigned to the next user for another time period. The previously served user is placed at the end of the waiting queue so it can be served in the next round. This algorithm continues in the same manner [18]. Fig. 5 illustrates the resource sharing between two users with TD RR algorithm. The colors and the line orientation make the difference between the users. In this example, every user is allocated 100% of the RBs and 50% of the time resource, so each gets 50% of the global resource [6]. The TD WRR differentiates from TD RR in the number and the type of users served.

Let us suppose a CBR (Constant Bit Rate) service of 500 kbps and a SNR (Signal to Noise Ratio) throughput per RB given by the radio conditions of 1 Mbps. Assuming there is one static user making the service and the same SNR is experienced in each RB and in all TTIs, the maximum amount of data that can be sent during 1 TTI per RB is 1 kb.

TABLE I. TYPICAL NUMBER OF PUCCH REGIONS

Bandwidth (MHz)	Number of 0.5 ms RBs sub-frame	Number of PUCCH regions
1.4	2	1
3	4	2
5	8	4
10	16	8
20	32	16

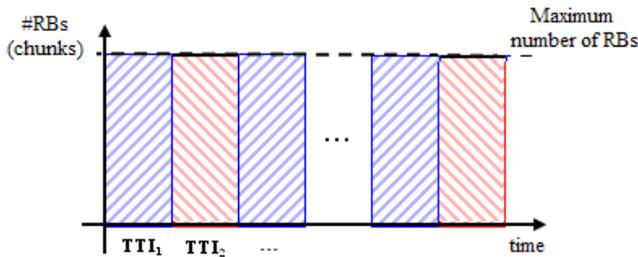


Figure 5. Resource sharing between two users with TD RR

Considering the system bandwidth of 20 MHz, which consists of 100 RBs, the user needs to be allocated all resources for five TTIs to reach his service throughput. Therefore the user must be allocated 1/200 of the total resource in order to be served. This ratio is equal to service throughput / (SNR throughput * total number of RBs given by the system bandwidth). This represents the main idea in the TD RR model.

B. Time and Frequency Domain Round Robin and Weighted Round Robin scheduling model

The FD RR allows multiple users to be scheduled within one TTI in cyclic order. Keeping in mind the PDCCH limitation discussed in Section II, the scheduling framework from Fig. 2 can be applied. The TDPS (Time Domain Packet Scheduling) may select N users in RR fashion to be scheduled in one TTI, but the PDCCH resources (M) must be checked in order to see if all users selected by the TDPS can be simultaneously scheduled. M users at most can be the input of FDPS (Frequency Domain Packet Scheduling), which schedules each user with RR strategy across different RBs. In the next TTI the users that were not selected in the previous one will be scheduled in the same manner and so on [6].

The FD RR is briefly presented in [19] where PDCCH constraint is not considered. The authors propose that all users be allocated one RB before reallocating to the same user. If the number of users waiting to be scheduled is less than the number of PDCCHs per TTI, this approach is correct, but only for LTE downlink (as in uplink the RBs must be adjacent). But if the number of users selected within one TTI is greater than the number of configurable PDCCHs and if the idea of allocating one RB to each user is maintained, the result will be a waste of resources [6].

The resource sharing between two users with FD RR, assuming a hypothetical system bandwidth of two RBs, is depicted in Fig. 6. As in Fig. 5, each user is allocated 50% of the global resource.

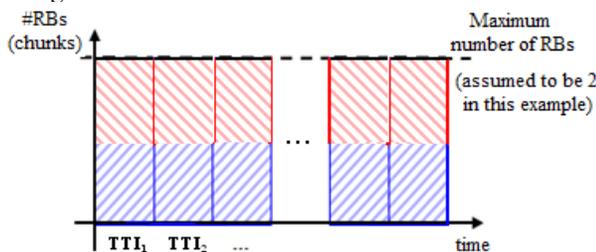


Figure 6. Resource sharing between two users with FD RR

Taking the example given in Section III.A, but considering the limitation of 20 PDCCHs per TTI for downlink LTE as it is concluded from [11], [14] and [15] and 40 users having the same radio conditions and making the same service, one user needs to be allocated 1 RB for 500 TTIs [6]. The global resource in this case is reduced due to PDCCH constraint i.e. the maximum throughput given by the radio conditions * number of PDCCHs. The radio resource ratio assigned to each user is 1/40, higher than in TD RR example, so the capacity will be smaller.

A solution to address this problem would be the allocation of more RBs at once to each user in order to exploit all transmission bandwidth [6].

Knowing that for 20 MHz band in downlink LTE 20 users can be simultaneously scheduled at most, each user can be allocated 5 RBs before assigning resources to another one. In this case, the FD RR cell throughput in LTE downlink will be the same as for TD RR, with the only advantage of being more suited to services with small packets and some delay requirements [6].

The FD RR cell throughput in LTE uplink will be less than that in TD RR due to the limitation in the actual transmission bandwidth brought by PUCCH.

As it was previously mentioned for TD WRR, the FD WRR has an impact on the number and types of users served, but the main principle is that from FD RR.

V. SIMULATION SCENARIOS AND RESULTS

A computer simulation using C++ platform is conducted to evaluate the performance of RR and WRR scheduling in downlink and uplink LTE, based on the mathematical modeling of these scheduling strategies, along with the basic network parameters. For the simulations performed a single cell eNodeB is considered, with a carrier frequency of 2.6 GHz FDD (Frequency Division Duplex) and a system bandwidth of 20 MHz.

Besides SISO (Single Input Single Output) antenna configuration used in [6], in this paper we also consider MIMO 2x2 and we present several simulation results for LTE uplink using SIMO (Single Input Multiple Output) 1x2. Moreover, in several scenarios the users are uniformly distributed in the cell compared to the results presented in [6], which treated the case of all users experimenting the same radio conditions.

In the simulations considering SISO in LTE downlink category 1 terminals are used with ~10 Mbps, in those with SIMO 1x2 in LTE uplink it is assumed that all users have category 3 terminals with ~50 Mbps, while in those with MIMO 2x2 category 3 terminals with ~100 Mbps are chosen.

In order to reduce the complexity of the system simulations, we assume that equal downlink transmit power is allocated on each RB, all transmitted packets are received correctly and the users are static. For LTE uplink scenarios, we also assume that the UE transmit power can sustain the entire bandwidth allocation to a single user during 1 TTI.

The downlink SNR values for SISO case used in this paper, resulting from pathloss, shadow fading, multipath fading, eNodeB transmit power and thermal noise, are listed

in Table II, along with the corresponding modulation and coding schemes and data rates. The downlink SNR values for MIMO 2x2 are listed in Table III and those for SIMO 1x2 for LTE uplink in Table IV.

The following sub-sections present the simulation results for cell throughput, average user throughput and system capacity in downlink and uplink LTE with RR and WRR

scheduling models. There are two categories of users considered: the first makes a CBR streaming service (e.g. video streaming) with a certain expected throughput (under this value the users cannot be served) and the second makes a VBR best effort service (e.g. data transfer using File Transfer Protocol) with a defined minimum accepted throughput, but it can reach more. The maximum best effort throughput reached is limited by the minimum between the data rate corresponding to the SNR experienced and the maximum throughput given by the user terminal category.

For all simulation scenarios, the FD RR scheduling model considered is the one with 1 RB allocation to each user before reallocating another one to other user. The reason for this choice stands in emphasizing the PDCCH impact on simultaneously served users that also leads, in certain situations, in cell throughput limitation.

TABLE II. DOWNLINK SNR TO DATA RATE MAPPING FOR SISO

Minimum downlink SNR values (dB)	Modulation and coding scheme	Data rate (kbps)
1.7	QPSK (1/2)	138
3.7	QPSK (2/3)	184
4.5	QPSK (3/4)	207
7.2	16 QAM (1/2)	276
9.5	16 QAM (2/3)	368
10.7	16 QAM (3/4)	414
14.8	64 QAM (2/3)	552
16.1	64 QAM (3/4)	621

TABLE III. DOWNLINK SNR TO DATA RATE MAPPING FOR MIMO 2X2

Minimum downlink SNR values (dB)	Data rate (kbps)
3	207.8
9	383.6
12	518.2
16	734.9
19	898.6
21	992.0
24	1086.0
26	1124.4

TABLE IV. UPLINK SNR TO DATA RATE MAPPING FOR SIMO 1X2

Minimum uplink SNR values (dB)	Data rate (kbps)
1	88.5
3	177.0
6	265.6
8	354.2
10	425.0
12	487.0
14	499.0
17	506.6

A. Cell throughput results for LTE downlink with SISO

These results have been previously presented in [6].

A 2 Mbps expected throughput is chosen for streaming users and the same value is considered as the minimum throughput for best effort users. It is assumed that all users experience the same radio conditions.

Fig. 7 and Fig. 8 show the cell throughput with TD RR and FD RR for streaming users and best effort users.

The dependence of the cell throughput on the SNR values with 30 users in the cell is depicted in Fig. 7. An interesting evolution is shown by the cell throughput in FD RR for streaming service, where the cell saturation is reached. The explanation lies in both PDCCHs limitation of 20 per TTI and the CBR service of 2 Mbps. Despite the PDCCH limitation in FD RR for best effort users, cell saturation is not reached due to their capability of achieving a higher throughput compared to their service throughput. All 30 users are served only in TD RR for the last SNR throughput value.

Considering that the users experience only the last SNR value from Table II, the cell throughput is evaluated with the number of users in the cell trying to reach their service. When comparing TD RR with FD RR based on the results illustrated in Fig. 8 it can be concluded that for best effort users they show the same cell throughput evolution. Despite the PDDCH limitation, the best effort users may achieve a higher throughput than the minimum defined one.

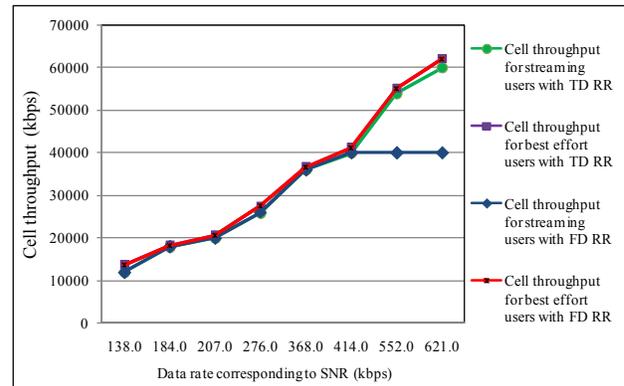


Figure 7. Cell throughput vs. SNR in LTE downlink with SISO for TD RR and FD RR

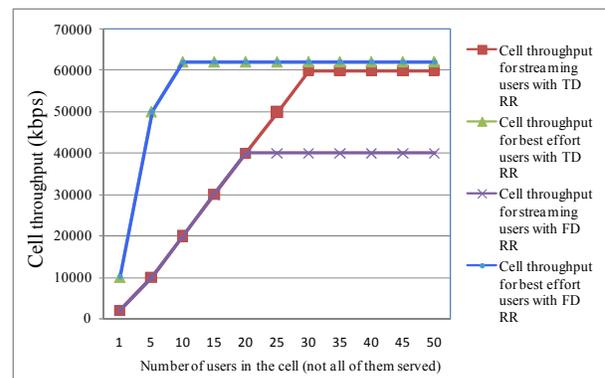


Figure 8. Cell throughput vs. the number of users in the cell in LTE downlink with SISO for TD RR and FD RR

This is not the case for streaming users because in TD RR the cell throughput is higher due to a higher number of users served. From the cell throughput saturation it can also be seen that in TD RR there are 31 streaming users served, while in FD RR only 20 users reach their service requirements (the maximum 20 PDCCHs that can be configured within 1 TTI does not necessarily limits the number of served users in the cell to 20; for a lower expected throughput, the number of users served is more than 20 in FD RR with one 1 RB allocated to each user, as it will be presented in the scenarios concerning MIMO 2x2 in LTE downlink and SIMO 1x2 in LTE uplink).

B. Average user throughput results for LTE downlink with SISO

Fig. 9 shows the evolution of average user throughput with the number of users in the cell (experiencing the same radio conditions as in Fig. 8). For streaming service the user throughput is constant at 2 Mbps, while for best effort users it varies until the cell saturation is reached, the saturation point being the maximum number of users served. The maximum best effort user throughput in the case of 1 and 5 users in the cell is limited by the terminal category at 10 Mbps. The achievable best effort user throughput is higher in FD RR than in TD RR for more than 20 users in the cell because there are fewer users served and the cell resource is shared between a smaller number users.

All the results presented so far were obtained considering separately streaming and best effort users, not mixed. The following Section presents the case with traffic mix and cell capacity evaluation.

C. System capacity results for LTE downlink with SISO

Fig. 10 and Fig. 11 show for both scheduling strategies how many users are served from the total number of users in the cell and the impact of the priority set for streaming service on the number and types of users scheduled. Half of the users in the cell are best effort users. The cell saturation is reached for 31 users served in TD RR and 20 in FD RR. When no priority is set (TD and FD RR), the number of served streaming users is equal to that of best effort users.

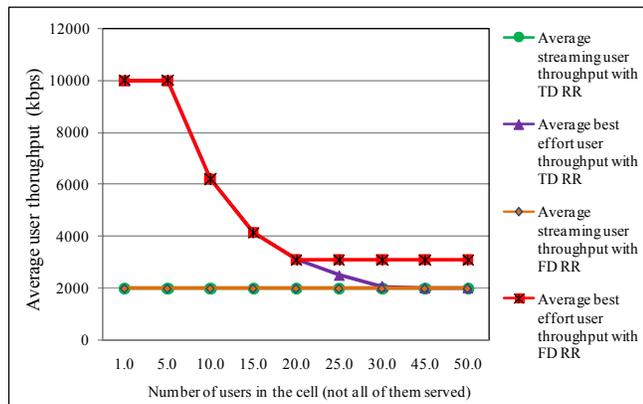


Figure 9. Average user throughput vs. the number of users in the cell in LTE downlink with SISO2 for TD RR and FD RR

For 50 users in the cell, in TD WRR there are 6 best effort users and 25 streaming users served, while in FD WRR there is no best effort user served and 20 streaming users served. The following sub-sections present simulation results that were not included in [6].

D. Cell throughput results for LTE downlink with MIMO 2x2

The results presented in sub-sections D, E and F were obtained through simulations of various scenarios considering MIMO 2x2 antenna configuration and 2 Mbps as the expected throughput for streaming users and 500 kbps as the minimum throughput for best effort users. Similar to SISO case, the cell throughput is evaluated for all SNR values from Table II and for several numbers of users in the cell. The dependence of the cell throughput on the SNR values with 50 users in the cell is depicted in Fig. 12. As in SISO scenario, in FD RR for streaming service the maximum cell throughput is limited to a value that in this case is equal to 40 Mbps.

The explanation lies in both PDCCHs limitation of 20 per TTI and the CBR service of 2 Mbps. But there is a major difference between this figure and Fig. 7 regarding the cell throughput in FD RR for best effort users.

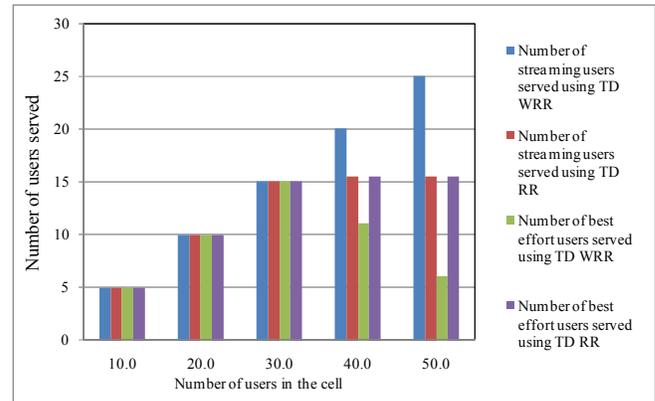


Figure 10. Number of users served vs. number of users in the cell in LTE downlink with SISO for TD RR and TD WRR

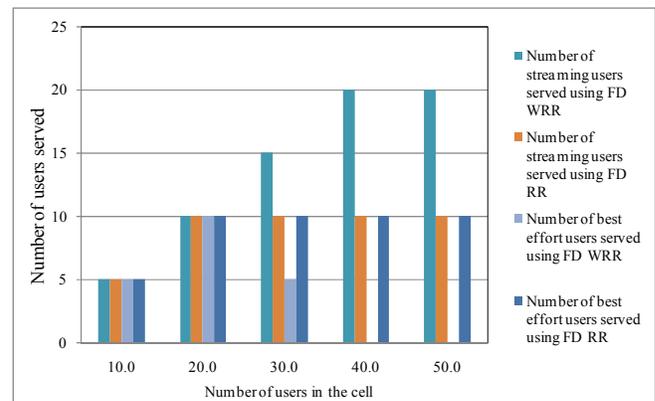


Figure 11. Number of users served vs. number of users in the with SISO for FD RR and FD WRR

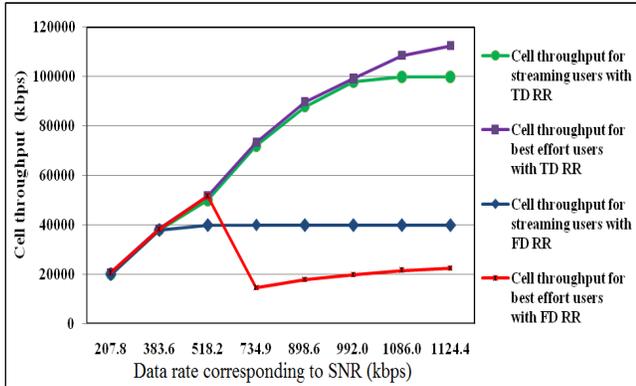


Figure 12. Cell throughput vs. SNR in LTE downlink with MIMO 2x2 for TD RR and FD RR

Because the best effort service requires a lower minimum throughput (500 kbps compared to 2 Mbps from previous scenario), there can be more than 20 users served in the cell for the last 5 SNR values. While in TD RR all 50 streaming and best effort users are served in the case where users experience the best radio conditions of those presented in Table II, in FD RR only 45 best effort users are assigned resources to get the required service. This emphasizes the poor performance of FD RR with 1 RB assigned and imposes the use of FD RR with more RBs assigned (e.g. 5 RBs) that has the same results as TD RR, but is more suited for power limited scenarios, low traffic or services with certain latency requirements.

The cell throughput evolution with the number of users, considering all users in the best radio conditions, is depicted in Fig. 13. Compared to Fig. 8, cell throughput for TD RR and FD RR, in the case of best effort traffic only, does not show the same evolution. This is due to the fact that in this case FD RR strategy allows more than 20 users in the cell to be served (45), thus limiting to 20 the effective number of RBs to be assigned to users every TTI (as 20 MHz bandwidth has 100 RBs and the maximum number of PDCCHs per TTI is 20).

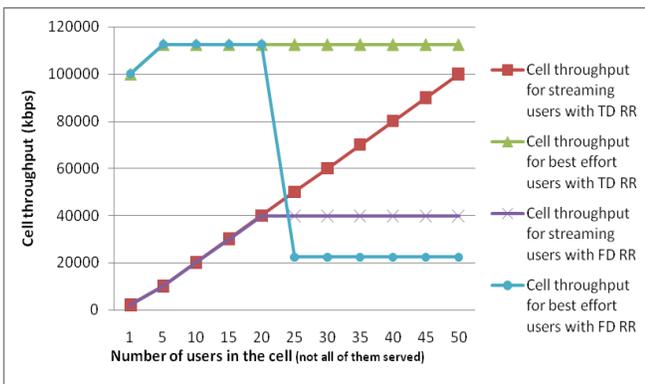


Figure 13. Cell throughput vs. the number of users in the cell in LTE downlink with MIMO 2x2 for TD RR and FD RR for users experiencing the best radio conditions

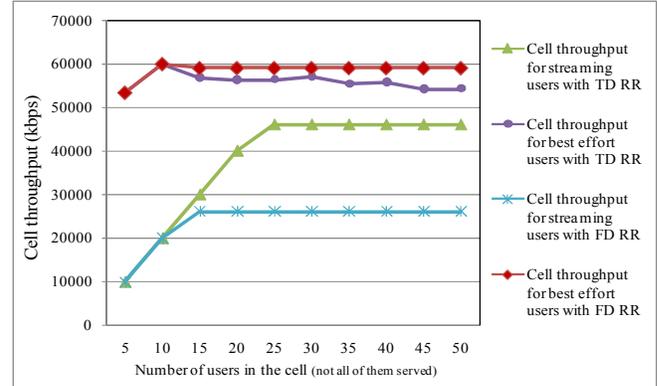


Figure 14. Cell throughput vs. the number of users in the cell in LTE downlink with MIMO 2x2 for TD RR and FD RR for users uniformly distributed in the cell

For streaming traffic only, the cell throughput with TD RR is higher than in FD RR due to a higher number of users served in the first case. In FD RR the maximum cell throughput is limited to 40 Mbps due to PDCCH, while in TD RR the cell throughput reaches 100 Mbps.

The cell throughput evolution with the number of users when the users are uniformly distributed in the cell, thus experiencing different radio conditions, is illustrated in Fig. 14. The number of PDCCHs in this case will be less than 20 per TTI because it will be a mix of PDCCH formats (40% Format 0, 30 % Format 1, 20 % Format 2 and 10% Format 3) [11], not only format 0, as considered so far. It results ~13 PDCCHs per TTI for downlink. Comparing Fig. 14 with Fig. 13, the maximum cell throughput value is the first difference to be noticed. As expected, in the scenario for Fig. 14, which is closer to a real one as different users experience different radio conditions, cell throughput barely exceeds 60 Mbps. And this is the case for best effort users that expect a lower throughput than the streaming users. In the latter case, the cell throughput reaches 46 Mbps, meaning 23 streaming users served. With FD RR, there are less than 20 users accepted that make streaming traffic or best effort traffic. More specifically, in this scenario, with FD RR only 13 streaming users are served vs. 20 in the previous scenario and 13 best effort users vs. 45 are allowed to make the traffic required.

E. Average user throughput results for LTE downlink with MIMO 2x2

The evolution of average user throughput with the number of users in the cell when users experience the best radio conditions is depicted in Fig. 15. For streaming service the user throughput is constant at 2 Mbps (as imposed by streaming service requirements), while for best effort users it varies, and cell saturation is reached for 45 users with FD RR. Comparing TD RR with FD RR in the case of best effort traffic only, besides the fact that with

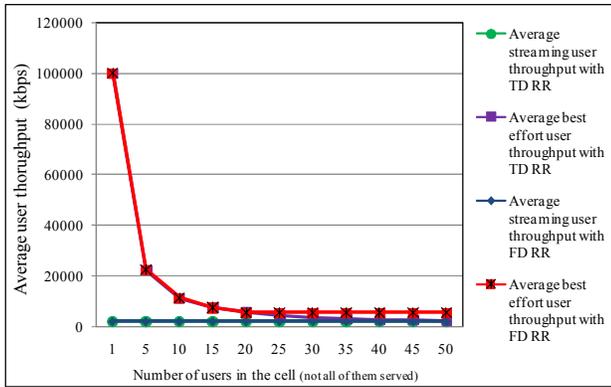


Figure 15. Average user throughput vs. the number of users in the cell in LTE downlink with MIMO 2x2 for TD RR and FD RR for users experiencing the best radio conditions

TD RR all 50 best effort users are served, the best effort user throughput for all 45 users is 2249 kbps with TD RR and 500 kbps with FD RR.

The average user throughput for both TD RR and FD RR with one type of users in the cell (streaming or best effort) when the users are uniformly distributed in the cell is depicted in Fig. 5.16. A comparison between Fig. 16 and Fig. 15 is necessary in order to outline the decrease in average user throughput when the users are uniformly distributed in the cell versus the case where all users were experiencing the best radio conditions. For 5 users in the cell it was obtained ~11 Mbps vs. ~23 Mbps. Similar to the previous case, in FD RR the average user throughput is higher than the one with TD RR (less users served, the cell resources divided between fewer users).

F. System capacity results for LTE downlink with MIMO 2x2

Fig. 17 and Fig. 18 show for both scheduling strategies how many users are served from the total number of users in the cell and the impact of the priority set for streaming service on the number and types of users scheduled. Half of the users in the cell are best effort users and the simulation is performed taking the last SNR value from Table II.

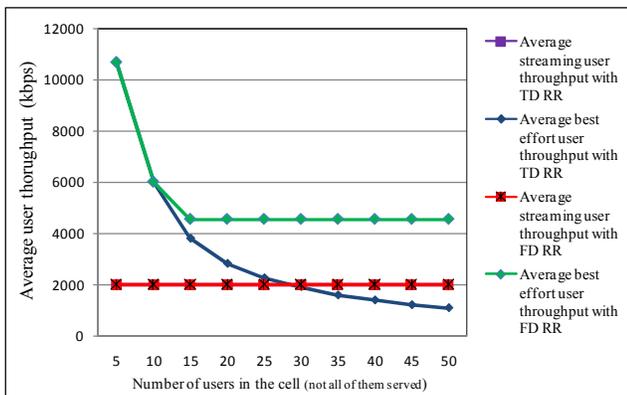


Figure 16. Average user throughput vs. the number of users in the cell in LTE downlink with MIMO 2x2 for TD RR and FD RR for users uniformly distributed in the cell

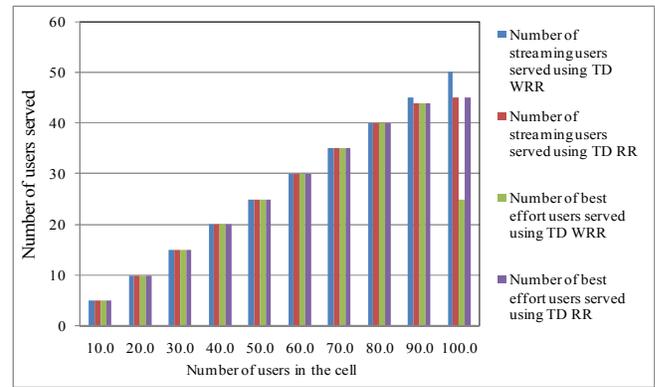


Figure 17. Number of users served vs. number of users in the cell in LTE downlink with MIMO 2x2 for TD RR and TD WRR

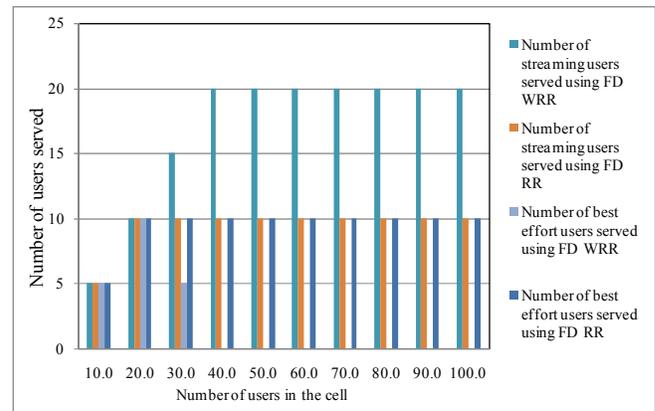


Figure 18. Number of users served vs. number of users in the cell in LTE downlink with MIMO 2x2 for FD RR and FD WRR

When no priority is set (TD RR and FD RR), the number of served streaming users is equal to that of best effort users. For 100 users in the cell and priority set (WRR), in TD WRR there are 25 best effort users and all 50 streaming users served, while in FD WRR there is no best effort user served and 20 streaming users served. These results emphasize the waste of resources generated by FD RR strategy with only 1 RB allocated to each user.

G. Cell throughput results for LTE uplink with SIMO 1x2

The following sub-sections present the simulation results for LTE uplink. For uplink performance evaluation, it was chosen a scenario with 1x2 SIMO, 20 MHz system bandwidth, with best effort and streaming users having category 3 terminals (~50 Mbps). For streaming service it is defined a constant throughput of 1 Mbps, while for best effort service a minimum throughput of 200 kbps.

It has to be reminded the uplink control overhead mentioned in Section III and specified in Table I that limits the actual transmission bandwidth. Also, the single-carrier property of uplink transmission cannot be neglected and in order to assure adjacent RBs in FD RR in the scenarios with up to 20 users in the cell, the users are assigned from the start with a several number of RBs (instead of 1 to each user before reassigning to the first one).

The cell throughput evolution with SNR values is shown in Fig. 19. 50 users were considered in the cell trying to reach the service. As for the first two SNR values, only 20 users best effort users can be served in FD RR, the cell throughput values are equal to those in TD RR (the cell resources are fully utilized). For the other SNR values, there can be more best effort users served in FD RR, but due to the minimum throughput of 200 Kbps and the PDDCH limitation, the transmission bandwidth is limited to 20 RBs (considering that the FD RR with 1 RB allocated to each user). The cell throughput for streaming service in FD RR is limited to 20 Mbps, also due to PDDCH constraint.

Fig. 20 illustrates the cell throughput evolution with the number of users in the cell in the best radio conditions scenario. As in Fig. 13, the FD RR cell throughput for best effort traffic drops when there are more than 20 users in the cell due to the transmission bandwidth limitation to 20 RBs (given by the PDDCH constraint). As expected, the cell throughput with FD RR with streaming users is limited to 20 Mbps (20 users served), while in TD RR 42 streaming users make the required service. The TD RR throughput is higher than the FD RR one when there are more than 20 users in the cell.

H. Average user throughput results for LTE uplink with SIMO 1x2

Fig. 21 illustrates the average user throughput evolution with the number of the users in the cells, the simulation being made with the highest SNR value.

The streaming user throughput was expected to be 1 Mbps, while an interesting evolution is seen in FD RR with best effort traffic: for less than 20 users in the cell, the cell resources are fully utilized and the users get a high throughput, while for more than 20 users the RBs that can be allocated are limited to 20 and in the case of 50 best effort users trying to reach their service, they are all served, but with 203 kbps. With TD RR strategy, all 50 best effort users are served, the minimum service throughput acquired being 851 kbps.

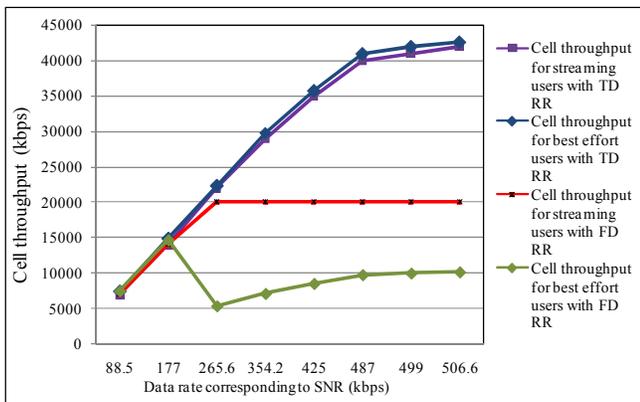


Figure 19. Cell throughput vs. SNR in LTE uplink with SIMO 1x2 for TD RR and FD RR

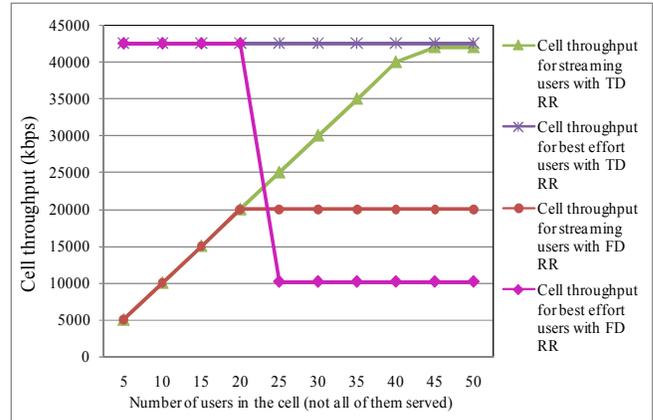


Figure 20. Cell throughput vs. the number of users in the cell in LTE uplink with SIMO 1x2 for TD RR and FD RR

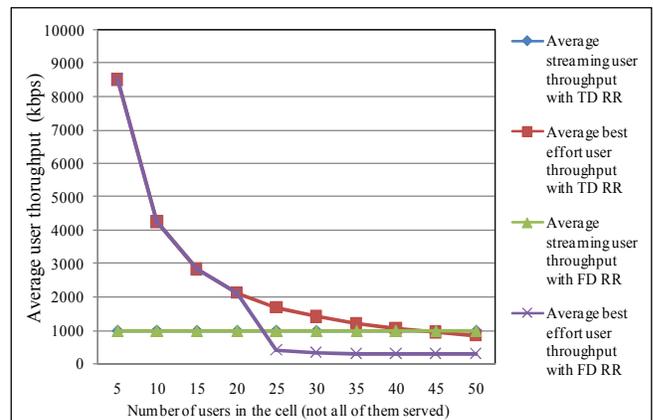


Figure 21. Average user throughput vs. the number of users in the cell in LTE uplink with SIMO 1x2 for TD RR and FD RR

I. System capacity results for LTE uplink with SIMO 1x2

All the previous results for LTE uplink have been obtained considering, in turn, streaming and best effort users. This Section presents the case with traffic mix and evaluates cell capacity with RR and WRR.

Fig. 22 and Fig. 23 show for RR and WRR scheduling algorithms, in TD and FD, how many users of a certain service category are served from the total number of users in the cell. All users are assumed to be experiencing the highest SNR value from Table III. Half of the users in the cell are best effort users.

For TD RR and FD RR the number of served streaming users is equal to that of best effort users. For 80 users in the cell, in TD WRR all 40 streaming users are served, but only 7 best effort users are accepted, while in FD RR all best effort users are rejected. In the case of equal priorities between streaming and best effort service (TD RR and FD RR) for 80 users in the cell, with TD RR there are 35 streaming and 35 best effort users served, and with FD RR 10 users of each category are rejected.

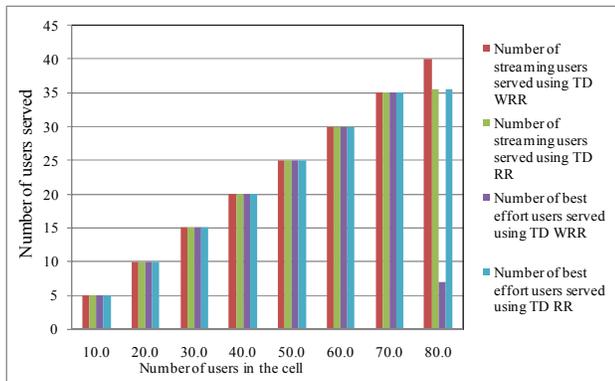


Figure 22. Number of users served vs. number of users in the cell in LTE uplink with SIMO 1x2 for TD RR and TD WRR

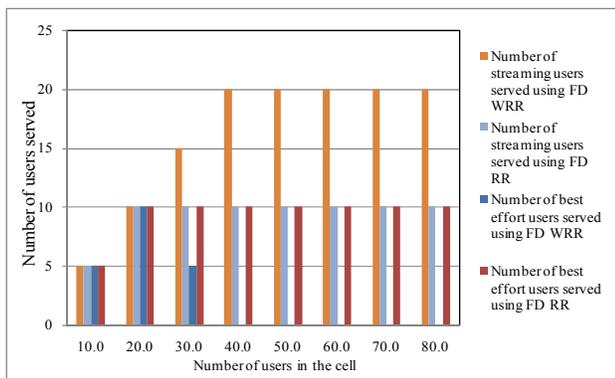


Figure 23. Number of users served vs. number of users in the cell in LTE uplink with SIMO 1x2 for FD RR and FD WRR

VI. CONCLUSIONS AND FUTURE WORK

This paper evaluates the performance of LTE downlink and uplink in what concerns cell throughput, average user throughput and cell capacity using two scheduling models in various scenarios of antenna configurations, radio conditions, number of users and service categories. The constraint of PDCCHs on the number of users scheduled each TTI, both for LTE downlink and uplink, has also been outlined and depicted in the simulation results, making FD RR with 1 RB assigned to each user less efficient when the number of users in the cell is higher than the PDCCHs. It was also discussed the limitation in the actual number of RBs in the transmission bandwidth brought by the uplink control channels. Taking into account that the mobile terminal is power limited and may not be able to support the assignment of the entire system bandwidth, the FD RR with more than 1 RB per user per TTI is more suited.

Despite its limitations, these scheduling models can offer an image of the LTE network performance and may be a useful tool to design an optimized LTE network, the most important aspect being the cell capacity evaluation with certain minimum or expected service throughput. Certain scenarios presented in this paper have been replicated in other simulation environments and the results obtained were similar to those presented in Section V.

Future work will focus on the analysis of LTE network performance using Opnet simulator as it offers some performance indicators evolution in time, latency results and more complex traffic mix scenarios.

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