Scheduling strategies for LTE uplink with flow behaviour analysis

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Abstract. Long Term Evolution (LTE) is a cellular technology developed to support diversity of data traffic at potentially high rates. It is foreseen to extend the capacity and improve the performance of current 3G cellular networks. A key mechanism in the LTE traffic handling is the packet scheduler, which is in charge of allocating resources to active flows in both the frequency and time dimension. In this paper we present a performance comparison of two distinct scheduling schemes for LTE uplink (fair fixed assignment and fair work-conserving) taking into account both packet level characteristics and flow level dynamics due to the random user behaviour. For that purpose, we apply a combined analytical/simulation approach which enables fast evaluation of performance measures such as mean flow transfer times manifesting the impact of resource allocation strategies. The results show that the resource allocation strategy has a crucial impact on performance and that some trends are observed only if flow level dynamics are considered.

1 Introduction

The 3rd Generation Partnership Project (3GPP) just recently finalized the standardization of the UTRA Long Term Evolution (LTE) with Orthogonal Frequency Division Multiple Access (OFDMA) as the core access technology. One of the key mechanisms for realizing the potential efficiency of this technology is the packet scheduler, which coordinates the access to the shared channel resources. In OFDMA-based LTE systems this coordination refers to both the time dimension (allocation of time frames) and the frequency dimension (allocation of subcarriers). These two grades of freedom, together with particular system constraints, make scheduling in LTE a challenging optimization problem, see [5].

Most research on LTE scheduling has been treating the downlink scenario, some examples being [8, 14]. Considerably less work has been dedicated to the uplink, where the transmit power constraint of the mobile equipment plays an important role. The LTE uplink scheduling problem can in general be formulated as a utility optimization problem, see e.g. [4, 7, 11]. The complexity of this optimization problem depends of course on the utility function that is considered (mostly aggregated throughput maximization). Still other aspects, among which fairness requirements (e.g. short- or long-term throughput fairness) and specific system characteristics (e.g. regarding fast fading, multiple antennas), when taken into account [6, 9, 10, 12] have shown to influence the complexity of the problem. As the optimal solutions would mostly be too complex for practical implementation the proposed scheduling algorithms are often based on heuristics yielding reasonable system performance under practical circumstances, see e.g. [2, 15].

Most papers consider the performance (resulting throughputs) of newly proposed scheduling schemes for scenarios with a fixed number of active users in the system (split up in different user classes depending on their channel characteristics). Studies that take into account the randomness of user behaviour, leading to a time varying number of ongoing flow transfers, are lacking. Filling this gap, in the present paper we study the performance of different LTE uplink scheduling schemes for scenarios where initiations of finite sized file transfers occur at random time instants and locations. We focus on the impact that flow's behaviour has on the performance observed by the users while also accounting for the user's location in the cell. The design of an optimal scheduling scheme is outside our scope.

In the present paper we focus on a class of resource fair scheduling schemes, where the active users are scheduled in a Round Robin fashion and are all assigned an equal number of subcarriers to transmit their traffic. However, it is noted that our analysis approach sketched below is in principle applicable for any uplink scheduling scheme in OFDMA-based networks.

Our modelling and analysis approach is based on a time-scale decomposition and works, at high level, similar to the approach we used previously in the context of UMTS/EUL, see [3]. It consists basically of three steps. The first two steps take the details of the scheduler's behaviour into account in a given state of the system, i.e. the number of active users and their distance to the base station. In particular, in the first step the data rate at which a user can transmit when scheduled is determined, taking into account the number of allocated by the scheduler subcarriers. The second step determines an active user's average throughput in the given system state by accounting for the total number of users present in that state. In the third step these throughputs and the rates at which new users become active are used to create a continuous-time Markov chain, which describes the system behaviour at flow level. From the steady-state distribution of the Markov chain the performance measures, such as mean file transfer time of a user, can be calculated.

For some special cases of our resource fair scheduling schemes the steady-state distribution of the Markov chain describing the system behaviour at flow level is solved analytically yielding insightful closed-form expressions for the mean file transfer times. For other cases simulation is used to derive the steady-state distribution. As the jumps in the Markov chain are related only to flow transfers and not packet level events, simulation is a very attractive option and does not suffer from the long running times of 'straightforward' detailed system simulations.

The rest of the paper is organized as follows. Section 2 provides a general discussion on LTE uplink scheduling and introduces the different resource fair scheduling schemes that we will analyse in this paper. In Section 3 we describe the considered network scenario and state the modelling assumptions. Subsequently, in Section 4 the performance evaluation approach is described in detail. Section 5 presents and discusses numerical

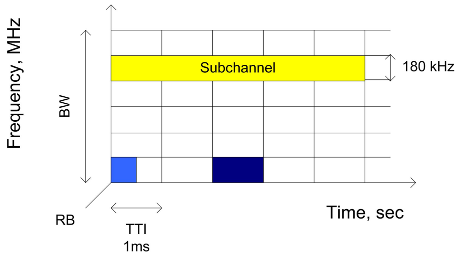


Fig. 1. Radio resource structure in LTE networks.

results illustrating the performance of the different scheduling schemes and the impact of the flow level dynamics. Finally, in Section 6, conclusions and our plans for future work are given.

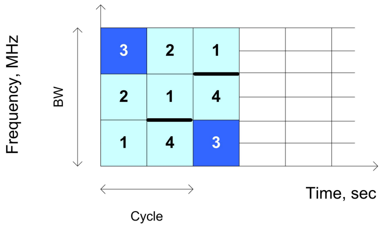
2 Scheduling

In this section we first give a general introduction to scheduling in LTE uplink, necessary for the understanding of the proposed schemes and our modelling choices, and introduce the notation. Subsequently, the proposed scheduling schemes are described.

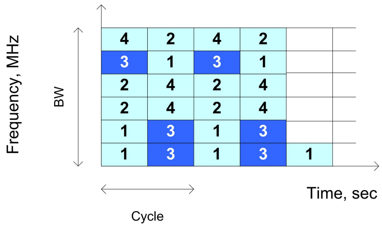
2.1 LTE Uplink Scheduling

The radio access technology chosen for the LTE uplink - SC-FDMA (Single Carrier - Frequency Division Multiple Access) - is a modified version of an OFDMA (Orthogonal FDMA) technology (used in LTE downlink), in which the radio spectrum is divided into nearly perfect mutually orthogonal subcarriers. In contrast to e.g. CDMA-based EUL, simultaneous transmissions from different mobile stations (MSs) do not cause intra-cell interference or compete for a share in the available uplink noise rise budget, but rather the transmissions compete for a share in the set of orthogonal (intra-cell interference-free) subcarriers. The total bandwidth that can be allocated to a single MS depends on the resource availability, the radio link quality and the terminal's transmit power budget.

A key feature of packet scheduling in LTE networks is the possibility to schedule users in two dimensions, viz. in time and frequency. The aggregate bandwidth BW available for resource management is divided in subcarriers of 15 kHz. Twelve consecutive subcarriers are grouped to form what we refer to as a 'subchannel', with a bandwidth of 180 kHz, as illustrated in Figure 1. Denote with M the number of subchannels offered by the available bandwidth BW. In the time dimension, the access to the subchannels is organized in time slots of 0.5 ms. Two slots of 0.5 ms form a TTI (Transmission Time Interval). The smallest scheduling unit in LTE is the intersection of a 180 kHz subchannel with a 1 ms TTI, which consists of two consecutive (in the time domain) *resource blocks* (RB). For simplicity of expression, in the rest of this paper we will use the term resource block to refer to a combination of two consecutive RBs. Hence in each TTI, the scheduler can assign M resource blocks over the active flows.



(a) Fair fixed assignment scheme



(b) Fair work-conserving scheme

Fig. 2. Scheduling schemes for an LTE uplink.

Scheduling decisions are taken by the base station, termed eNodeB in LTE, each TTI and are potentially based on channel quality feedback provided by the MSs. The packet scheduler decides which users are served and how many resource blocks are assigned to each selected user. As mentioned before, this assignment is restricted by the requirement that resource blocks assigned to any given user must be consecutive in the frequency domain. The transmit power applied by any given MS is equally distributed over the assigned resource blocks, see [15]. Hence, then a higher assigned number of resource blocks implies a lower transmit power per resource block. This has obvious implications for the signal-to-interference-plus-noise ratio (SINR) experienced at the eNodeB, see Section 4. Note that the data rate that a user can realize depends on both the number $M(MS)$ of assigned resource blocks and $SINR$ experienced per resource block, which determines the applied MCS (modulation and coding scheme). This issue is discussed in more detail in Section 5.2.

The rate r is additionally affected by practical limitations, see [1]. On the one side, the $SINR$ is lower bound to a minimum target level, necessary for successful reception. On the other side, the rate per RB is upper bound by the MCS. In our case we work with 16QAM since it should be supported by all terminals but potentially also 64QAM can be used (with limited terminal support).

2.2 Scheduling Schemes

In our analysis we concentrate on *resource fair* scheduling schemes, which assign equal resource shares to all active users, independently of their respective channel conditions. More specifically, we consider two distinct schemes termed *fair fixed assignment* (FFA) and *fair work-conserving* (FWC). These scheduling schemes are specified in more detail below, supported by the illustrations in Figure 2, which considers a scenario with four active users.

The first scheduler is termed *fair fixed assignment* because it assigns the same, a priori specified, number of resource blocks to each active user (see Figure 2(a)). The number of assigned resource blocks, denoted $M(MS)$ is an operator-specified parameter. If the number N of active users is such that the total number of requested resource blocks is less than the available number of resource blocks per TTI, i.e. if $N \cdot M(MS) < M$, then a number of resource blocks are left idle. Naturally this reflects a certain degree of resource inefficiency in the scheme, especially for situations with low traffic load and hence few active users. When the number of active users is such that $N \cdot M(MS) > M$, then not all users can be served in each TTI and hence it may take several TTIs to serve all users at least once. We define the *cycle length* as the number of TTIs necessary to serve all users at least once, as indicated in the figure. This cycle length can be expressed as $c = max(1, N \cdot M(MS)/M)$, which is not necessarily integral (but at least one), in which case the start of a given cycle may fall within the same TTI as the end of the previous cycle.

The second scheme, the *fair work-conserving* scheme, aims to avoid the resource inefficiencies of the FFA scheme under low traffic loads, while still preserving the resource fairness property. The scheme's objective is to distribute the available resource blocks evenly over the active users within each individual TTI. As result the FWC scheduler is optimal in the class of resource-fair Round Robin schedulers. In principle each user is assigned M/N resource blocks in each TTI. Since M/N need not be integral, in an implementable version of the FWC scheduler, a scheduling cycle is defined of multiple TTIs during which user-specific resource block assignments appropriately vary between $\lfloor M/N \rfloor$ and $\lceil M/N \rceil$ in order to, on average, achieve the fair assignment of M/N resource blocks. More specifically, the cycle length is equal to the smallest integer c such that $c \cdot M/N$ is integral, which is at most equal to N.

3 Model

We consider the scenario of a single cell with radius r. The cell is divided in K zones of equal area in order to differentiate between user's distance to the base station. Each zone is characterized by a distance d_i measured fron the outer edge of the zone. Mobile stations are uniformly distributed over the cell zones and flow arrivals follow a Poisson process with rate λ. Hence the arrival rate per zone (due to equal area) can be derived as $\lambda_i = \lambda/K$, where $i = 1...K$. The distribution of the active users over the zones of the cell we term *state* $\underline{n} = n_1, n_2...n_K$.

All mobile stations are assumed to have the same maximum transmit power capacity P^{tx}_{max}. Each user distributes this maximum power level equally over the RBs it gets assigned leading to transmit power per RB $P^{tx}_i = P^{tx}_{max}/M_i(MS)$. Note that in the discussed scheduling schemes $M_i(MS)$ is the same for all zones but other schedulers, where this is not the case, are possible. Due to the different distance d_i each zone is characterized by distinctive path loss $L(d_i)$, where $i = 1...K$. We apply a Hata 321 path loss model for the path loss (in dB), according to which

$$L(d_i) = PL_{fix} + 10alog_{10}(d_i) \tag{1}$$

where PL_{fix} is a parameter that depends on system parameter such as antenna height and a is the path loss exponent. In the rest of the paper linear scale is used for $L(d_i)$. Users belonging to the same zone have the same distance d_i and hence experience the same path loss. At this stage of the research we consider only thermal noise N_0 from the components at the base station. Neither shadowing nor fast fading have been considered. Note that intra-cell interference can be assumed to be effectively zero due to the orthogonality of the subcarriers in LTE. As we consider a single cell, inter-cell interference is not taken into account in the current model.

Given a known path loss, the received power (per zone) at the eNodeB P_i^{rx} can be expressed as

$$P_i^{rx} = \frac{P_i^{tx}}{L(d_i)} \tag{2}$$

Eventually, for the signal-to-noise ratio measured at eNodeB from user of zone i we can derive:

$$SINR_i = \frac{P_i^{rx}}{N_0} = \frac{P_i^{tx}}{L(d_i)N_0} = \frac{P_{max}^{tx}/M_i(MS)}{L(d_i)N_0} \tag{3}$$

Recall that it should hold that $SINR_i \geq SINR_{min}$ for each zone.

4 Analysis

Our proposed evaluation approach, as discussed earlier, consists of three steps. First we perform packet level analysis, which accounts for scheduler specifics and system characteristics. The so termed instantaneous rate is defined and is later used at step two to derive a state-dependent throughput that accounts for the effect of the number of MSs in the system and their position, i.e. the system state. Eventually, at step three a Markov model is set up to model the long term performance of the schedulers. From the steady state distribution of the model we can derive flow level performance measures such as mean flow transfer times (MFTT) T_i. These steps are explained in more detail below.

4.1 Instantaneous Data Rates

The data rate realized by a user when it is scheduled is what we term *instantaneous rate* r_i. It is determined by the *SINR* as derived above, the possible coding and modulation schemes and the receiver characteristics related to that MCS. The instantaneous rate is calculated over all RBs that are allocated to a particular user. In our analysis we use the Shannon formula modified with a parameter σ to represent the limitations of implementation, see Annex A in [1]. Hence for the instantaneous rate we can write:

$$r_i = (M_i(MS) * 180kHz)\sigma log_2(1 + SINR_i) \tag{4}$$

Note that both $SINR_i$ and r_i are calculated over the same RB allocation.

In the FFA scheme (with a fixed number of RB allocation per user in a cycle) the instantaneous rate of a particular MS is always the same when the MSs is served. In the case of the FWC scheme however the instantaneous rate depends on the total number of users in the system. In particular, it depends on whether low or high allocation, see Section 2.2, occurs and hence for the FWC scheme we calculate two instantaneous rates $r_{i,L}$ and $r_{i,H}$ respectively.

4.2 Flow Level Analysis

Depending on the number of active MSs it may happen that several TTIs are necessary to serve all MSs once, i.e. cycle length ¿ 1 TTI. In such situations the instantaneous rate does not represent correctly the performance of a particular MS since it is only realized every several TTIs. A better metric is necessary - one which accounts for the active number of users in the cell and which we term *state dependent throughput* $R_i(\underline{n})$. In the case of FFA scheduler the state dependent throughput can be easily expressed as $R_i(\underline{n}) = r_i/c$. For the FWC scheme we need to consider the variation in low resource block allocation ($\lfloor M/N \rfloor$ blocks) and high resource block allocation ($\lceil M/N \rceil$ blocks). Each allocation exhibits for a fraction of the scheduling cycle as follow:

$$\text{Low allocation } a_L = \frac{M}{N} - \left\lceil \frac{M}{N} \right\rceil \tag{5}$$

$$\text{High allocation } a_H = \frac{M}{N} - \left\lfloor \frac{M}{N} \right\rfloor \tag{6}$$

Eventuallty for the state dependent throughput we can write:

$$R_i(\underline{n}) = a_L r_{i,L} + a_H r_{i,H} \tag{7}$$

State dependent throughputs reflect performance for a particular system state. In order to observe the system under changing number of users we propose to set up a Markov model for each of the schemes, which to represent the system (cell) dynamics in a long term. The division of the cell in K zones results in a K-dimensional state space, each dimension reflecting the number of flows in a zone. A state in the model corresponds to a system state $\underline{n}$ and in each dimension i transition rates are determined by flow arrivals λ_i/K and flow departures $R_i(\underline{n})/F$, where F is the mean of the exponentially distributed flow size.

From the steady-state distribution of the Markov chain we can derive long term performance metrics such as mean flow transfer times. The distribution can be found by simulating the model, more precisely the state transitions. In special cases - for a Markov chain of a well studied class - the distribution can be given by explicit closed-form expressions. In our study the model of the FFA scheduler appeared to be a M/M/1 processor sharing (PS) model with state dependent service rates, which we will discuss below. The model of the FWC scheduler has a more complex form and is not trivial to solve, which is why we selected a simulation approach for it.

M/M/1 PS with State Dependent Service Rates In the case of FFA scheduler the Markov chain belongs to the class of M/M/1 processor sharing models with state dependent service rates and multiple customer classes, see [13]. For such model the mean sojourn time T_i of a users of zone i requiring an amount τ of service is given by (e.g. see [13]):

$$T_i = \tau_i \frac{\sum_{j=0}^{L-1} \frac{\rho^j}{j!} + \frac{L^L}{L!\rho} \left((\rho/L)^{L+1} \frac{L}{1-\rho/L} + (\rho/L)^{L+1} \frac{1}{(1-\rho/L)^2} \right)}{\sum_{j=0}^{L} \frac{\rho^j}{j!} + \frac{L^L}{L!} (\rho/L)^{L+1} \frac{1}{1-\rho/L}} \tag{8}$$

where $L = BW/M(MS)$ is the maximum number of users that can be served in a TTI, given a RB allocation strategy. Note that the impact of the distance of each zone is taken in the specific flow size $\tau_i = F/r_i$, expressed in time.

Table 1. Maximum RB allocation

Zone number	1	2	3	4	5	6	7	8	9	10
Distance, km	0.32	0.45	0.55	0.63	0.71	0.77	0.84	0.89	0.95	1
$M(MS)_{max}$	50	50	50	30	20	15	11	8	7	6

The system load ρ for the discussed situation can be defined as $\rho = \sum_{i=1}^{K} \rho_i$ where $\rho_i = \lambda_i F / r_i$ is the load per zone. The stability condition of the system being $\rho \leq L$, we can derive the maximum arrival rate that the system can support, namely

$$\lambda = \frac{L}{F} \frac{K}{\sum_{j=1}^{K} \frac{1}{r_i}} \tag{9}$$

The relation between the arrival rate and the RB allocation is further numerically examined in Section 5.4.

5 Numerical results

In this section we present a quantitative evaluation of the two LTE uplink schedulers introduced in Section 2.2. We investigate how flow level performance is affected by the choice of RB allocation. Beforehand we will present the parameter settings and certain preliminary numerical results that support the better understanding of the discussed evaluation scenarios.

5.1 Parameter Settings

The cell is divided in ten zones with cell radius of 1km. Given an equal zone area, the corresponding distances of the different zones are given in Table 1. A system of 10 MHz bandwidth is studied, which, given that a RB has 180 kHz bandwidth, results in maximum of 50 RBs available per TTI.

Mobile stations have maximum transmit power $P^{tx}_{\max} = 0.125$ Watt. The lower bound on the SINR (per RB) is -10dB while the upper bound on performance is determined by a 16QAM modulation that corresponds to SINR of 15dB. For the path loss we have used the expression $L(d) = 141.6 + 10alog_{10}(d,km)$ based on path loss exponent of $a = 3.53$, height of the mobile station 1.5m, height of the eNodeB antenna 30m and system frequency 2.6GHz. The thermal noise per subcarrier (180kHz) is -121.45dBm and with noise figure of 5dB the effective noise level per resource block is $N = -146.45dB$. The attenuation of implementation σ is taken at 0.4, see [1] and Equation 4. The average file size F is 1Mbit and the arrival rate changes depending on the discussed scenario.

5.2 Preliminaries

In this section we discuss three relevant issues: (i) the limitations on performance posed by the minimum required $SINR_{min}$; (ii) the system stability condition; and (iii) the correlation between RB allocation and realized instantaneous rates.

Table 2. Maximum flow arrival rate

$M(MS)$	1	2	3	4	5	6	7	8	9	10
L	50	25	16	12	10	8	7	6	5	5
Max λ	4.79	2.89	1.9922	1.5582	1.3338	1.09	0.9643	0.8343	0.7	0.703

$SINR_{min}$ sets an upper bound $M(MS)_{max}$ on the number of RBs that can be assigned to a user. Since the transmit power of a MS is spread over its assigned RBs, increasing the RB allocation leads to lower transmit power per RB and hence decreasing SINR. Naturally this maximum allocation differs per zone, which is shown in Table 1. Even if assigned more than its maximum RB allocation, a MS will not use it all leaving RBs unused and potentially leads to utilization inefficiency.

Continuing with the second issue, from the stability conditions in Section 4.2, i.e. $\rho \leq L$, it follows that more RBs per MS results in lower maximum supported arrival rate by the system. Table 2 presents the relation between number of RBs, the maximum possible number of MSs in a TTI L and the maximum supported arrival rate λ. Note that the maximum arrival rate for FWC scheme is similar to the maximum for the FFA scheme with a single RB.

Finally, Figure 3(a) shows the changes in instantaneous data rates for a range of RB allocations in the case of a single user. Four scenarios corresponding to distance from the base station (0.1 0.25 0.5 0.87)km are examined. As Equation 4 suggests, increasing the RB allocation leads to increase in the realized data rates. However, MSs close to the eNodeB benefit more from high allocation than remote MSs. For remote users $SINR_{min}$ constrains the maximum usable RB allocation hence limiting performance gains. This trend is well illustrated by the quickly flattening graph for 0.5km and the terminating graph of 0.87km (after 15 RBs the MS is no more able to reach the required $SINR_{min}$).

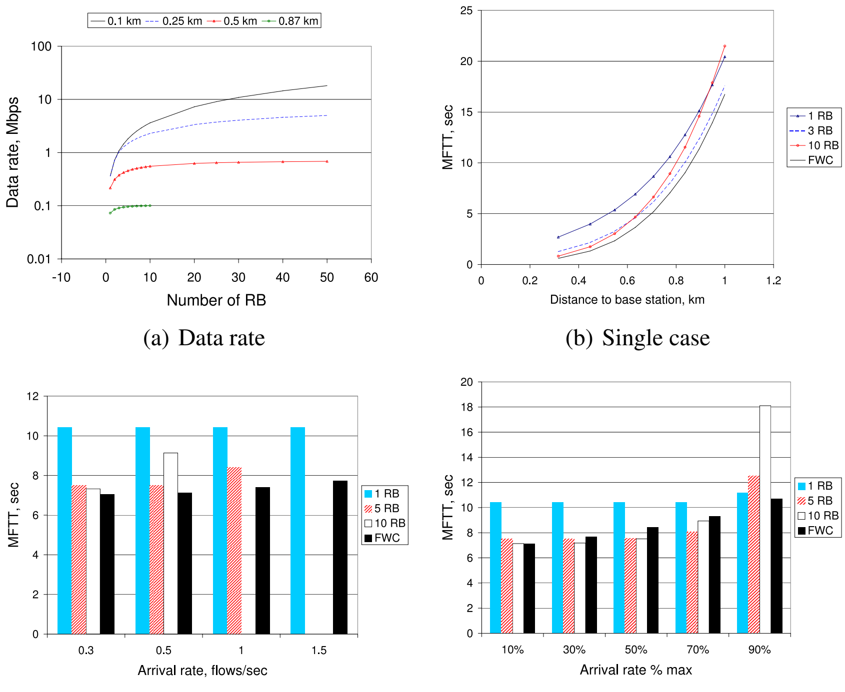
5.3 Impact of RB allocation

In this evaluation scenario we extend the investigation on the impact of RB allocation - both in terms of number of assigned RBs and of allocation strategy - towards the flow level. We compare mean flow transfer times for the particular arrival rate of 0.5 flows/sec. The number of assigned RBs in the FFA scheme changes from one to three to ten[3]. and the results are shown in Figure 3(b).

How the number of assigned RBs affects performance is observed for the FFA scheme. The general trend is that increase in allocation translates to lower MFTT, e.g. one vs. three RBs. However, for remote MSs high allocation worsens performance, i.e. ten vs. three RBs. While close-by MSs have sufficient power capacity to reach $SINR_{min}$ for all allocations remote users lack this ability (due to high path loss). They use less RBs such that to guarantee $SINR_{min}$ but the unused by them RBs are still allocated thus effectively decreasing state dependent throughputs.

The impact of the allocation strategy is investigated by comparing the one RB FFA with the FWC scheme, see Figure 3(b). The particular choice is dictated by the similar

[3] These showed to be the most interesting assignments within the range one to ten RBs with a step of one.



(a) Data rate (b) Single case

(c) Range case (d) Load progression

Fig. 3. Performance evaluation scenarios for: (a) relation between RB allocation and deliverable data rates for a single user; (b) impact of RB allocation on flow level performance for a particular arrival rate; (c) impact of arrival rate on flow level performance; and (d) flow level performance for a range of system loads.

realized load by both schemes, i.e. about 6% of the maximum load. Note that equal arrival rate means equal traffic offered to the system but not equal system load (which depends on RB assignment). Due to its inefficient utilization for low loads (it leaves RBs unassigned, see Section 2.2) the FFA scheme is outperformed by the FWC scheme (which assigns all RBs over the active users).

5.4 Impact of System Arrival Rate

Figure 3(c) shows the MFTT for a range of arrival rates, i.e. (0.3, 0.5, 1, 1.5) flows/sec. Again the FWC outperforms the FFA scheme. It is more interesting that system capacity changes (decreases) for different (increasing) RB allocation. For example, ten RBs allocation is not feasible already at arrival rate of 1 flows/sec while the three RBs allocation at 1.5 flows/sec.

Furthermore the optimal choice of RB allocation also differs per arrival rate. Figure 3(c) shows that few RBs, e.g. five, become beneficial for higher arrival rate compared to many RBs, e.g. ten. With high load cycle lengths bigger than one are more probable, in which case the inherent inefficiency of the FFA scheme for remote users starts to affect flow level performance, see Equation 7. An effect that is strengthened by the fact that remote users stay longer in the system.

Also notice that the one RB FFA is not affected at all by the arrival rate for the presented range. Since the system load is relatively low compared to the maximum the number of users is such that still all of them fit in the same TTI hence leading to unchanged performance.

5.5 Impact of System Load

In this section we investigate performance for a range of specifically chosen arrival rates $X\%\lambda_{max}$ where $X\%$ is chosen between (10%,30%,50%,70% and 90%). The so selected arrival rates correspond to a particular system load scenario, e.g. low, medium or high load. Note that the maximum arrival rate λ_{max} differs per RB allocation, see Section 5.2. The results are presented in Figure 3(d).

The results indicate that the choice of best RB allocation is load specific. For low loads (10% and 30% λ_{max}) we see that more resource blocks are beneficial while for high load (70% and 90% λ_{max}) the contrary holds - a single RB allocation provides better service. On the one side, the utilization inefficiency of the FFA scheme for remote users exhibits more for high loads due to the big number of active users, including cell edge users. These stay relatively long in the system and virtually occupy RBs, causing degradation in state dependent throughputs. On the other side, many MSs with few RBs per MS but high transmit power per RB result in higher accumulated energy per TTI than few MSs where each MS gets assigned many RBs. This is particularly true about MSs at the cell edge.

It is interesting to note that although FWC outperforms the FFA scheme the gain decreases in $X\%$ and for high loads the performance is very similar.

6 Conclusion

In this paper we present an indicial investigation on the impact that flow dynamics (changing number of users) have on performance given the complex scheduling environment of LTE uplink. We argue that flow dynamics are crucial for the understanding and selection of a scheduler. Two low complexity scheduling schemes are examined - both designed to provide equal channel access. We propose a hybrid modelling and analysis approach which combines packet level analysis with flow level simulation. The approach allows to capture diverse features of users and system, supports fast evaluation and scales well. Indeed the numerical results show that certain performance trends can be observed only if flows' behaviour is considered. The conclusions apply for a single cell scenario and accounting for user's limited transmission power and system's constrains on signal strength.

Currently we are extending our flow level performance evaluation to account for the practical limitation on the maximum number of users that can be served in a TTI, see [5]. Additionally it would be interesting to consider a scheduling scheme which maximizes the delivered performance but might be less fair is the provided service.

References

1. 3GPP TS 36.942. LTE; evolved universal terrestrial radio access (E-UTRA); radio frequency (RF) system scenarios.
2. M. Al-Rawi, R. Jntti, J. Torsner, and M. Sagfors. On the performance of heuristic opportunistic scheduling in the uplink of 3G LTE networks. Proceedings PIMRC 2008, 2008.
3. D.C. Dimitrova, J.L. van den Berg, G. Heijenk, and R. Litjens. Flow level performance comparison of packet scheduling schemes for UMTS EUL. WWIC '08, 2008.
4. L. Gao and S. Cui. Efficient subcarrier, power and rate allocation with fairness considerations for OFDMA uplink. volume Vol. 7, pages 1507–1511. IEEE Transactions on Wireless Communications, 2008.
5. H. Holma and A. Toskala. *LTE for UMTS, OFDMA and SC-FDMA Based Radio Access*. John Wiley & Sons, 2009.
6. J. Huang, V.G. Subramanian, R. Agrawal, and R. Berry. Joint scheduling and resource allocation in uplink OFDM systems for broadband wireless access networks. volume Vol. 27, pages 226–234. IEEE Journal on Selected Areas in Communications, 2009.
7. K. Kim, Y. Han, and S. L. Kim. Joint subcarrier and power allocation in uplink OFDMA systems. volume Vol. 9, pages 526–52. IEEE Communications Letters, 2005.
8. Raymond Kwan, Cyril Leung, and Jie Zhang. Multiuser scheduling on the downlink of an LTE cellular system. *Rec. Lett. Commun.*, 2008:1–4, 2008.
9. S. B. Lee, I. Pefkianakis, A. Meyerson, S. Xu, and S. Lu. Proportional fair frequency-domain packet scheduling for 3GPP LTE uplink. IEEE INFOCOM 2009 mini-symposium, 2009.
10. L.A. Maestro Ruiz de Temino, G. Berardinelli, S. Frattasi, and P. Mogensen. Channel-aware scheduling algorithms for SC-FDMA in LTE uplink. Proceedings PIMRC 2008, 2008.
11. H. G. Myung, J. Lim, and D.J. Goodman. Single carrier FDMA for uplink wireless transmission. volume Vol. 48, pages 30–38. IEEE Vehicular Technology Magazine, 2006.
12. C. Ng and C. Sung. Low complexity subcarrier and power allocation for utility maximization in uplink OFDMA systems. volume Vol. 7, pages 1667–1675. IEEE Transactions on Wireless Communications, 2008.
13. R. D. van der Mei, J. L. van den Berg, R. Vranken, and B. M. M. Gijsen. Sojourn times in multi-server processor sharing systems with priorities. volume 54, pages 249–261. Performance Evaluation, 2003.
14. C. Wengerter, J. Ohlhorst, and A. G. E. von Elbwart. Fairness and throughput analysis for generalized proportional fair frequency scheduling in OFDMA. Vehicular Technology Conference, 2005. VTC 2005-Spring, 2005.
15. E. Yaacoub and Z. Dawy. Centralized and distributed LTE uplink scheduling in a distributed base station scenario. Advances in Computational Tools for Engineering Applications, 2009. ACTEA '09, 2009.