New Frequency-Time Scheduling Algorithms for 3GPP/LTE-like OFDMA Air Interface in the Downlink

M. Assaad[1], A. Mourad[2]

[1]Ecole Superieure d'Electricite (SUPELEC), 3 Rue Joliot-Curie 91192 Gif-sur-Yvette, France
mohamad.assaad@supelec.fr
[2]Mitsubishi Electric (ITE-TCL), 1 allée de Beaulieu 35708 Rennes, France
mourad@tcl.ite.mee.com

***Abstract* — This paper proposes a new downlink frequency-time scheduling for 3GPP/LTE-like system. 3GPP/LTE DL is based on the OFDMA technique and uses several enhanced techniques such as Adaptive Modulation and Coding (AMC) and frequency-time scheduling to increase the spectral efficiency and aggregate throughput of the system. Scheduling technique consists in sharing efficiently the wireless channel in order to achieve a trade off between fairness and capacity. In OFDMA, scheduling and AMC can be implemented jointly or separately/sequentially (sequentially i.e. AMC after the scheduling). This paper proposes two novel schedulers that assume respectively a joint and separate implementation of scheduling and AMC. System simulation is conducted to compare the performance of the proposed schedulers. Results show that the first scheduler with separate AMC and scheduling implementation outperforms the second scheduler (with joint AMC implementation) in terms of trade off between fairness and capacity.**

I. INTRODUCTION

In radio communication systems, multiple users/applications are sharing the system resources. Examples of resources are time slots, frequency bands, codes, and antennas. In order to be satisfied, each user requires satisfaction of its Quality of Service (QoS) requirements. Hence, for satisfying multiple users with different services, the system should provide the capability of supporting a mixture of services with different QoS requirements.

The sharing structure of resources allows using so-called scheduling techniques. A scheduling technique is evaluated in terms of the maximum benefit the system can derive from given resources and the fairness in sharing the system resources among users. The benefit is measured by the system throughput and spectral efficiency, and fairness is measured by the degree of "meeting the data rate and the delay constraints of the different users". A scheduler has therefore two main objectives: First maximize the system benefit or efficiency by allocating the resources to the most appropriate users and second achieve fairness between the users. These two objectives are conflicting and there is a risk in achieving one at the expense of the other. A trade-off between fairness and efficiency should be achieved by the scheduler.

The problem addressed in this paper is how to schedule or allocate efficiently the resources to multiple users in the context of Orthogonal Frequency Division Multiple Access (OFDMA) air interface in the downlink. OFDMA is a very promising radio access technology that has been adopted for both uplink and downlink air interfaces of WiMAX fixed and mobile standards, namely IEEE802.16d and IEEE802.16e respectively [1][2], and more recently for the downlink air interface of the Third Generation Partnership Project (3GPP) currently normalizing the Long Term Evolution (LTE) of the third generation (3G) cellular system [3].

For the concern of resource allocation, OFDMA access technology can be seen as a two-dimensional resource sharing system. The first dimension is time and second dimension is frequency. Time resource units are commonly known as Transmission Time Intervals (TTI), and frequency resource units are referred to as chunks in 3GPP/LTE terminology. In 3GPP/LTE, a chunk is composed of a group of 12 OFDM sub-carriers. Two modes are adopted for mapping sub-carriers to chunks. In the first "localized" mode, adjacent sub-carriers are mapped to chunks with the aim of almost flat fading over each chunk. In contrast, the second "distributed" mode maps sub-carriers faraway over the whole bandwidth to each chunk in the aim of frequency diversity within the chunk. In the localized mode, a chunk is expected to experience specific propagation and interference conditions and thus a specific channel quality. This channel quality is quantified by so-called Channel Quality Indicator (CQI). The large variation of the CQI with respect to chunks makes the use of frequency scheduling greatly beneficial. Thus, in this context, the scheduling problem can be formulated as: *Having in hands the CQI values for all chunks fed back from all users, how to properly allocate the chunks to the users at each TTI in order to achieve a good balance between capacity and fairness*.

Although the scheduler can assign several chunks to one user at a given TTI, one Modulation and Coding Scheme (MCS) is attributed to the user. To select a given MCS scheme for a given user, the node B determines an equivalent (or effective) CQI from the CQI values of the chunks allocated to the given user. Consequently, scheduling disciplines that require the user's instantaneous rates for evaluating the scheduling metric need joint or parallel implementation of AMC and scheduling which results in a high complexity. AMC and Scheduling can be implemented separately or sequentially (i.e. AMC after the scheduling) if only the CQI values of chunks (and not the instantaneous rates) are needed for evaluating scheduling metric. Note that AMC and scheduling implementation issue has not yet attracted a lot of attention in literature even though it can have an impact on the system implementation complexity.

This paper proposes and compares the performance of two schedulers. The first one assumes a separate implementation of AMC and scheduling whereas the second algorithm needs joint AMC and scheduling implementation.

The rest of this paper is organized as follows. Section II presents an overview of state of the art solutions in the context of OFDMA systems. Section III describes our new frequency-time schedulers proposed in this paper. In section IV, the methodology for performance evaluation at the system level is presented. Then, numerical results are given in section V, and conclusions and perspectives are drawn in section VI.

II. OVERVIEW ON SCHEDULING IN OFDMA SYSTEMS

The problem of resource allocation in OFDMA systems has attracted an enormous research interest. Two classes of resource allocation schemes exist: fixed resource allocation [4] and dynamic resource allocation [5-9]. Fixed resource allocation assigns resources (e.g. time slots or sub-carriers) to users independently of the current channel conditions. This results in wasting system resources in the form of power or bit rate. Dynamic resource allocation adapts the quantity of resources assigned to users according to their instantaneous channel conditions. Three major approaches are used in designing dynamic resource allocation. The first approach is theoretical and complicated to implement. The two other approaches or classes are more suitable for implementation in practice however they do not achieve the best balance between fairness and capacity.

In [5-9], the problem of resource allocation is considered as a convex optimisation problem. Two strategies are used in the optimization: Margin Adaptive (MA) [5] and Rate Adaptive (RA) [6][7]. MA aims to minimize the overall power with respect to the user's rate or data error rate constraints. RA has the objective of maximizing the total transmitted rate with respect to the users' rate constraints. In most of the proposed studies, the convex optimization problem is solved by water-filling algorithm. In [9], the nonlinear optimization problem is transformed into linear problem and solved by Linear Integer Programming (LIP). Even though a lot of effort is made to reduce the optimization complexity of the dynamic resource allocation, the complexity is still great and the proposed solutions are not suitable for implementation in practical systems. In addition, these optimization problems assume a continuous objective function in continuous convex sets. In practice, optimization should consider discontinuous sets of rates available for users.

A second approach for solving the scheduling problem consists in dividing the problem into two sub-problems: sub-carrier allocation and sub-carrier assignment. The sub-carrier allocation problem consists in determining the number of sub-carriers to allocate to each user, while the sub-carrier assignment consists in assigning these sub-carriers to users based on the results of sub-carrier allocation problem. Several algorithms have been proposed in this direction. In [10-11], at least one sub-carrier is allocated to each user (to ensure fairness) and the remainder of sub-carriers is allocated based on the normalized queue state of each user (i.e. by dividing the queue state of the user by the overall queue state of all users). The sub-carriers are then assigned by attributing to each user the best current sub-carriers in a prioritized manner (circular order). In [12-13], the authors determine the number of sub-carrier to allocate to each user using an algorithm that balances the trade off between the channel state information and the packet delay information. The sub-carrier assignment problem is solved by an algorithm that monitors the violations of the maximal delay in all queues and by dividing the violations occurrences among all users. In [13], another sub-carrier assignment algorithm based on the exponential rule is also used.

A third approach for solving the scheduling problem consists in merely adapting the TDMA-based discipline for scheduling traffic over time varying channels to the case of OFDMA/TDMA resource allocation problem. In other words, it consists in using the same criterion of TDMA scheduling discipline on each sub-carrier. In [14], a Multi-carrier Proportional Fair (called MPF) scheduling is proposed. It consists in allocating each sub-carrier to the user the highest sub-carrier quality (in bit rate) relative to its average achieved rate. In [15], a similar algorithm is used where the sub-carrier is allocated to the user having the best sub-carrier quality relative to the ratio between the average achieved rate and the required bit rate. Other TDMA discipline scheduling, such as exponential rule proposed in [16], can be adapted to OFDMA system by considering the instantaneous rate on each sub-carrier. Note that this class of frequency scheduling needs in general a joint implementation of the AMC and scheduling procedures.

In this paper, two scheduling disciplines are proposed and compared. The first scheduler relies on the second class of dynamic resource allocation described above by decoupling sub-carrier allocation procedure from sub-carrier assignment. The sub-carriers allocation and assignment procedures are novels. This scheduler decouples also the scheduling procedure from AMC which results in lower implementation complexity. The second scheduler proposes a joint implementation of the scheduling and AMC procedures by updating the user's effective CQI and MCS at each sub-carrier assignment. This scheduler can be seen as a part of the third dynamic resource allocation class.

III. PROPOSED SCHEDULERS

In this section, the schedulers proposed in this paper are described.

A. *Scheduler 1*

This scheduler divides the resource allocation problem into two procedures: chunks allocation and chunks assignment. The chunks allocation procedure determines the number of chunks to allocate to each user based on the instantaneous channel conditions and user's average achieved rate. For this, the scheduler proceeds as follows:

Let $CQI_k^{(\ell)}$ be the channel quality indicator for k-th user on the ℓ-th chunk. The scheduler evaluates the effective CQI $ECQI_k$ of each user from the CQI values of all chunks. The corresponding bit rate Eff_rate_k to this effective CQI is then determined by attributing a given MCS to the user. This effective rate represents the user bit rate as when all the chunks are attributed to the user. If R_k is the average achieved bit rate of k-th user at given time t (NB: time index is omitted for the sake of clarity), $R_{k,\min}$ is the minimum bit rate required by user k and L is the total number of chunks, the number L_k of chunks to allocate to user k is then determined as:

$$L_k = \left\lfloor \frac{Eff\_rate_k}{\sum_{i=1}^{K} Eff\_rate_i} \frac{\frac{R_{k,\min}}{R_k}}{\sum_{j=1}^{K} \frac{R_{j,\min}}{R_j}} L \right\rfloor \qquad (1)$$

Where $\lfloor . \rfloor$ denotes the integer part. The $L - \sum_{k=1}^{K} L_k$ remainder chunks are then allocated to the users that have minimum number of allocated chunks L_k. This increases the degree of fairness of the scheduler. If two or more users have the same number of chunks, these users are classified by decreased order of their ratio $\frac{R_{k,\min}}{R_k}$. The remainder chunks are then allocated one by one as follows:

```
While number of remaining chunks > 0
        Find user k for which L_k is minimum;
        If several users have the same minimum L_k
                Find user k that has L_k minimum
                and minimum ratio $R_{k,\min}/R_k$;
        End (of If)
        L_k = L_k +1;
End (of While)
```

Once the number of chunks to allocate to users is determined, the chunks assignment procedure allocates then physically the chunks to users. Several algorithms can be used in this procedure (e.g. Max C/I, etc.). In order to balance the trade off between the fairness and cell throughput, we propose in this paper to use the following algorithm that classifies the chunks for all the users in decreased order of their ratio:

$$\frac{CQI_k^{(\ell)}}{\frac{1}{L}\sum_{i=1}^{L} CQI_k^{(i)}} \frac{CQI_k^{(\ell)}}{\frac{1}{K}\sum_{j=1}^{K} CQI_j^{(\ell)}} \qquad (2)$$

Thus, for each chunk ℓ, the algorithm starts by classifying the users by decreased order of their ratio given in (2). Then, it constructs a matrix of L rows and K+2 columns. The first column contains the maximum value of (2) with maximum taken over the users, the second column contains the chunk indexes, and the K-th other columns contain the users indexes classified by decreased order of their ratios (2). The table is then sorted by decreased order of the values of the first column.

The scheduler starts with the first element of the sorted table, thus by the chunk that has the maximum element in the first column of the table, i.e. the chunk with the maximum over the chunks of the maximum over the users of the ratio in (2). It attributes this chunk the user that achieves this maximum, i.e. the user that has its index in the third column of the table. If the number of chunks to allocate to this user (determined by the chunk allocation procedure) is already reached, the scheduler moves to the next user in table, i.e. the user that has its index in the fourth column in the table and so on until all the chunks are allocated to the users. The following algorithmic description gives better understanding of the algorithm:

```
For k =1 to K
        L_assigned (k) = 0;
        % L_assigned(k) is the number of chunks assigned to user k
End (of For k)

For i =1 to L
        user_index = Table(i,3);
        chunk_index = Table(i,2);
        j = 3;
        If L_assigned(user_index) = = L_allocated(userindex)
                j = j +1;
                user_index = Table(i,j);
                % if the number of assigned chunks is equal to the number
                determined by the chunks allocation procedure, we move
                to the next users.
        End (of If)
        Assign chunk(chunk_index) to user(user_index);
        % assign the chunk that has chunk_index to the user that has user_index
End (of For i)
```

After assigning all the chunks to the users, the effective CQI of each user is evaluated and a corresponding MCS with maximum instantaneous rate r_k is selected. The average achieved rate of the k-th user is then updated for scheduling at time t+1 as giving below:

$$R_k[t+1] = \left(1 - \frac{1}{t_c}\right) R_k[t] + \frac{1}{t_c} r_k[t] \qquad (3)$$

Where t_c is a smoothing average factor generally set to 1000.

B. Scheduler 2

The second scheduler proposed in this paper consists in adapting a TDMA scheduling discipline to OFDMA system. This scheduler needs a joint use of chunk assignment and AMC procedures. The scheduler allocates the chunks at time t in such a way to maximize the following utility function:

$$\max \sum_{k=1}^{K} \frac{\left(\frac{R_{k,\min}}{R_k}\right)}{\sum_{j=1}^{K} \left(\frac{R_{j,\min}}{R_j}\right)} r_k \qquad (4)$$

Where r_k and R_k are respectively the instantaneous rate and average achieved rate of user "k" at time t. For the sake of simplicity, we omit the time index t. It is important to note that this scheduler is somehow equivalent to the proportional fair scheduler with adaptation to OFDMA system since more than one user can be served at time t. This scheduler can be implemented as follows:

- **Classify the chunks in a decreased order similarly as in the chunks assignment procedure of the previous scheduler.**

- **Start with the first chunk, and assign the chunk to the user that maximizes the utility function defined above.**

- **Move to the next chunk, evaluate the effective CQI of each user and attribute a MCS to the user (based on the previous allocated chunk and the current chunk). Since the current chunk can be allocated to one of the *K* users, *K* possible values of the utility function are evaluated. The chunk is then allocated to the user that maximizes the utility function.**

- **Repeat this procedure for the other ($L-2$) chunks. For each chunk, *K* possible values of effective CQI and user's rate are evaluated and the chunk is assigned to the user that maximizes the utility function.**

As someone can remark, the AMC procedure is included in the scheduling algorithm. Once all the chunks are assigned, the instantaneous rate of each user is evaluated and the average achieved rate of user k is updated using equation (3).

IV. PERFORMANCE EVALUATON

Figure 1 gives a basic flowchart of the Monte-Carlo system level simulator used for evaluating the performance of proposed schedulers.

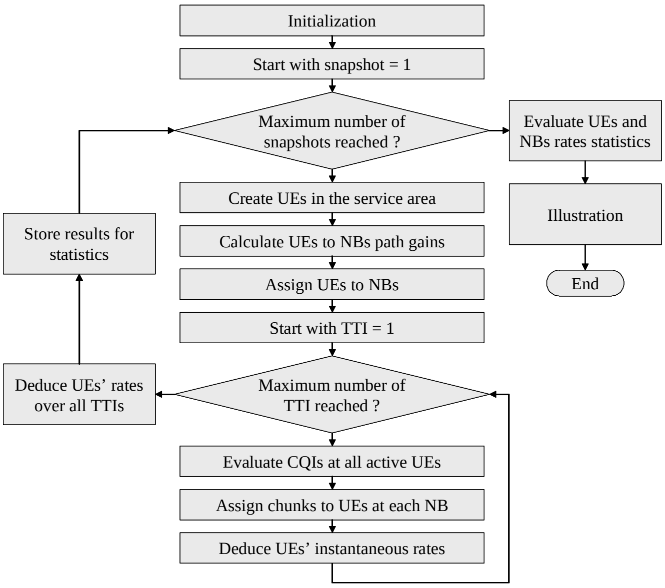

Figure 1: Flowchart of Monte-Carlo system level simulator used for performance evaluation.

Before starting Monte-Carlo simulation, an initialization phase sets all parameters related to both link and system levels, mainly, OFDMA physical layer configuration, small scale fading, cellular layout, antennas and transmission power, large scale fading, total number of users, and QoS profiles.

Then, a first loop starts on the number of snapshots. At each snapshot, the UEs positions are generated randomly within the service area following a uniform distribution. The multi-cellular environment is simulated with wraparound technique thus enabling collection of results from all Node Bs within the main cluster without bias caused by cell border effects. The path gains between all UEs and all NBs are then calculated. Path gain is the large scale fading component and it includes both distance decay and shadowing effects. Next, UEs are assigned to NBs according to maximum path gain criterion, i.e. a UE is assigned to the NB to which it has the maximum path gain. No macro-diversity handover is assumed. The main parameters of the system level simulation are provided in table 1.

Next, a new loop starts on the number of TTIs. At each TTI, the CQI over each chunk is evaluated for each active UE. The CQI value at n-th TTI associated with ℓ-th chunk for k-th active UE connected to q-th NB is determined as follows:

$$CQI_{k,q}^{(\ell)}[n] = \frac{P_q^{(\ell)} G_{k,q}^{(q)} \left| h_{k,q}^{(q,\ell)}[n] \right|^2}{\sum_{b=1, b\neq q}^{Q} P_b^{(\ell)} G_{k,q}^{(b)} + P_v^{(\ell)}} \qquad (5)$$

Where $P_b^{(\ell)}$ is the power transmitted by b-th NB on ℓ-th chunk, $G_{k,q}^{(b)}$ is the path gain between b-th NB and k-th UE connected to q-th NB, $P_v^{(\ell)}$ is the receiver noise power over ℓ-th chunk, and Q is the number of NBs in the main cluster. The coefficient $h_{k,q}^{(q,\ell)}[n]$ is representative of the fast fading affecting ℓ-th chunk at n-th TTI for the channel between k-th UE connected to q-th NB and serving q-th NB.

In (5), it should be pointed out that channel coefficients and interference plus noise level are assumed to be perfectly known. Furthermore, interference is assumed to come only from interfering NBs, i.e. we don't take into account interference that may result from the use of multiple antennas at the serving NB, and we only consider the interference level in average with respect to the fast fading for the channels between interfering NBs and interfered UE.

After evaluating the CQI values for all chunks and all active UEs, dynamic scheduling is performed for assigning chunks to UEs at each NB. The scheduling algorithms described in previous section are implemented. Next to scheduling, the UEs instantaneous rates for the optimal allocation are outputted for the purpose of performance analysis. The instantaneous rate at n-th TTI for k-th UE connected to q-th NB is obtained as:

$$r_{k,q}[n]=\max_{MCS}\left\{D_{MCS}\left(1-BLER_{MCS}\left(ECQI_{k,q}[n]\right)\right)\right\} \quad (6)$$

Where $ECQI_{k,q}[n]$ is the equivalent or effective CQI for the chunks allocated at n-th TTI to k-th user connected to q-th NB, $BLER_{MCS}$ is the Block Error Rate achieved with modulation and coding scheme MCS, and D_{MCS} is the MCS transmission rate. Equation (6) reflects Adaptive Modulation and Coding (AMC). Indeed, we assume a given number of modulation and coding schemes and the MCS used is that achieving the highest instantaneous rate for the given chunks allocation.

There are several forms for combining a given set of CQI values into one scalar effective CQI. Most advanced forms have been derived from performance analysis of the channel decoder. The most commonly used form in the state of the art is the Exponential Effective form. It is given by [17]:

$$ECQI_k=-\beta\log\left(\frac{1}{L_k}\sum_{\ell=1}^{L_k}\exp\left(\frac{-CQI_k^{(\ell)}}{\beta}\right)\right) \quad (7)$$

Where β is a calibration factor dependent on the MCS used and on the codeword length, hence on the number L_k of chunks allocated to the given UE. The advantage of the exponential effective CQI form lies in its capability of accounting properly for the selectivity of CQI values for prediction of instantaneous BLER. The BLER is directly predicted from exponential effective CQI through a look-up table (LUT) specific to the MCS used and the codeword length. The LUT is merely the mapping between BLER and Signal to Noise Ratio (SNR) over an Additive White Gaussian Channel (AWGN). It is obtained through link level simulations.

When the maximum number of TTIs is reached, the simulator stores the UEs' rates averaged over all TTIs. Then, another snapshot starts, and so on and so forth until reaching the maximum number of snapshots. Then at the end, the simulator outputs some statistics like for instance cumulative distribution function (CDF) of UEs' and NBs' rates.

V. NUMERICAL RESULTS

In order to compare between the performances of the proposed schedulers, we depict in figure 2 the Cumulative Distribution Function (CDF) of the user's average achieved bit rate. This CDF allows measuring the trade off between fairness and throughput since it shows the variation of the user's achieved rate around its average value. Figure 2 shows clearly that scheduler 1 achieves better trade off between fairness and throughput than scheduler 2. The cell throughput for scheduler 1 is around 14Mbps whereas it does not exceed 9Mbps for scheduler 2. Scheduler 2 achieves better fairness than scheduler 1 but as one can see in figure 2 the average user's bit rate is much lower for scheduler 2 than for scheduler 1.

Besides, scheduler 1 has a less implementation complexity than scheduler 2 since it does not need joint implementation of AMC and scheduling as we have explained throughout this paper.

More performance results for these schedulers will be presented in the final paper. The average and CDF of the user' throughput according to the user distance from the base station will be provided. The percentage of MCS use according to the user-base station distance will be presented also. More figures on the cell capacity/coverage will be provided as well.

Parameter description	**Value**
Cellular Layout	Hexagonal grid, 19 sites
Inter-site distance (ISD)	1000 m
Carrier frequency	2.0 GHz
Bandwidth	10 MHz
TTI	1 ms
Number of considered mobiles per cell	14
Link to System interface	EESM
Traffic model	FTP
Total node B power	43dBm
Antenna plus loss cable	14dBi
Thermal noise Power density	-174 dBm/Hz in 10MHz

Table 1: Main parameters of the system level simulation

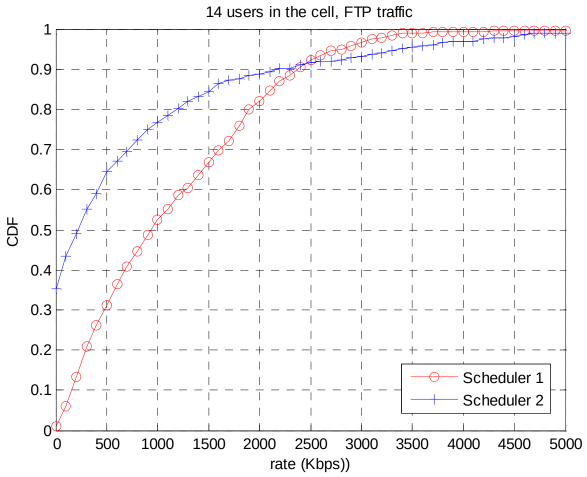

Figure 2: CDF of the user's achieved bit rate

VI. CONCLUSION

This paper provides analysis of the frequency-time scheduling technique in OFDMA system. Two novels schedulers that try to balance the trade off fairness and capacity are proposed. The first scheduler divides the scheduling problem into chunks allocation and chunks assignment procedures. The chunks are assigned to users based on the instantaneous chunk's CQI and user's average bit rate. This scheduler has a simple implementation since AMC technique is used once after the chunks assignment. The second scheduler assumes a joint implementation of AMC and scheduling. This scheduler allocates the chunks to users based on a utility function that depends upon the user's instantaneous and average bit rates. This scheduler has a more complicated implementation than the first scheduler. System level simulations show that the second scheduler results in boosting the fairness between users but at the expense of high cell throughput loss (loss of 35%). Consequently, the first scheduler achieves a better trade off between fairness and capacity than the second scheduler with low implementation complexity cost.

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