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

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***Abstract* — This paper proposes new frequency-time schedulers for 3GPP/LTE-like system in the downlink. 3GPP/LTE DL is OFDMA-based with Adaptive Modulation and Coding (AMC) and frequency-time scheduling to enhance spectral efficiency and aggregate system throughput. Time-frequency scheduling and AMC can be implemented jointly or separately i.e. sequentially AMC after scheduling. Two novel schedulers are proposed in this paper with respectively joint and separate implementation of scheduling and AMC. Through system level performance evaluation, 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 and implementation complexity.**

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.

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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

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:

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

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:

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

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:

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

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

B. Scheduler 2

The second scheduler 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.**

The scheduler makes a joint decision on the MCS to be used and chunks to be assigned to each user. 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

A. Performance Metrics

Three UE-oriented metrics are computed for performance evaluation: CQI per chunk, effective CQI over UE's assigned chunks, and UE's received instantaneous rate *r*.

The CQI for ℓ-th chunk and *k*-th active UE connected to *q*-th NB is determined at *n*-th TTI as:

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

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), the 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 between sectors 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. Note that full usage of the total bandwidth is assumed at each NB.

There are several forms for combining the CQI values corresponding to the UE's assigned chunks into one scalar effective CQI. Most advanced forms have been derived from performance analysis of the channel decoder. A commonly used form in the state of the art is the Exponential Effective form. It is given by [EES]:

$$ECQI_k = -\beta \log\left(\frac{1}{L_k}\sum_{\ell=1}^{L_k} \exp\left(\frac{-CQI_k^{(\ell)}}{\beta}\right)\right) \qquad (6)$$

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 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.

The instantaneous rate received at *n*-th TTI for *k*-th UE connected to *q*-th NB is obtained as:

$$r_{k,q}[n] = \max_{MCS}\left\{D_{MCS}\left(1 - BLER_{MCS}\left(ECQI_{k,q}[n]\right)\right)\right\} \qquad (7)$$

Where $ECQI_{k,q}[n]$ is the equivalent or effective CQI for the chunks assigned at *n*-th TTI to *k*-th UE 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 (7) reflects Adaptive Modulation and Coding (AMC). The MCS selected is that achieving the highest instantaneous rate for the given chunks allocation.

The system level simulator outputs statistics of all above UE-oriented performance metrics and also provides the total NB performance from the results from all UEs.

B. Numerical Results

The most relevant simulation parameters are summarized in Table 1, Table 2, and Table 3 for OFDMA link level configuration, MCS formats and system level configuration, respectively.

In order to compare between the performances of the proposed schedulers, we depict in figure 1 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 1 shows clearly that scheduler 1 achieves better trade off between fairness and throughput than scheduler 2. Most of the time, users have bit rates higher than 1Mbps if scheduler 1 is used. However, scheduler 2 results in starvation of the users at the cell border. In fact, approximately 20% of the users in the cell have bit rates less than 500kbps. Concerning the cell throughput, both of the schedulers allow achieving approximately the same cell throughput (22Mbps). This result can be interpreted by the fact that scheduler 1 uses two steps to allocate resources to users (subcarriers' allocation and subcarriers' assignment) whereas resources are allocated by scheduler 2 in one step. Therefore, scheduler 1 has a better control on the resource allocation procedure which results in boosting the fairness between users. In addition, the scheduling rule of scheduler 2 is more affected by the instantaneous bit rate which explains the huge loss of fairness.

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.

V. CONCLUSION

This paper provides analysis of frequency-time scheduling in OFDMA system. Two novel schedulers that try to balance the trade off between fairness and capacity are proposed. The first scheduler splits the scheduling problem into two procedures: chunks' allocation and chunks' assignment. 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 determined once after the chunks' assignment procedure. The scheduling rule of the second scheduler assumes a joint implementation of AMC and scheduling. This scheduler allocates the chunks to the users based on a utility function that depends upon the user's instantaneous and average bit rates. This scheduler has therefore a more complicated implementation than the first scheduler. System level simulations show that 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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Table 1: OFDMA air interface configuration.

OFDMA air interface configuration	
Bandwidth	10 MHz
Sampling frequency	15.36 MHz
FFT length	1024
Guard interval length	72 samples
# of non-zero sub-carriers	600
# of sub-carriers per RB	12
# of OFDM symbols per TTI	14
TTI length	1 ms
# of data symbols per RB	120
Multiple antenna context	SISO
Transmission mode	Localized

Table 2: MCS schemes with EES β parameter.

MCS	Modulation	Coding rate	EESM β
0	QPSK	1/3	2.3
1		1/2	2.9
2		3/4	2.4
3	16QAM	1/2	6.2
4		3/4	8
5	64QAM	1/2	12.6
6		3/4	27.1

Table 3: System level configuration.

System Configuration	
Lay-out	Hexagonal grid, 19 sites / 3 sectors
Inter-site distance	900 m
Carrier frequency	2 GHz
Traffic model	Full buffer (FTP)
# of UEs per sector	10
L2S interface	EESM
Node B Transmitter	
Total available power	43 dBm
Power assigned to Pilots/data	2 Watts/ up to 18 Watts
# of Tx antennas	1
Antenna gain plus cable loss	14 dBi
Antenna pattern	$\min\left(12\left(\frac{\theta}{70}\right),20\right) \quad ; \quad \theta(\deg)$
Propagation model	
Path loss	128 + 37.6*log10(R) ; R in Km
Shadowing standard deviation	8 dB
Correlation between sites	0.5
Fast fading	ITU vehicular A, 30 Km/h
Penetration loss	20 dB
Interference model	AWGN
UE receiver	
Thermal noise power density	-174dBm/Hz
Noise figure	9 dB
# of Rx antennas	1
Antenna gain	0 dBi
Antenna pattern	Omnidirectionnal
Channel estimation	Ideal
CQI reporting	Ideal
Turbo decoder (Duo-binary)	Max-log MAP with up to 8 iterations
Scheduling	
Transport formats	All MCS
RB allocation strategy	Frequency dependent
Ordering policy	Schedulers 1 and 2

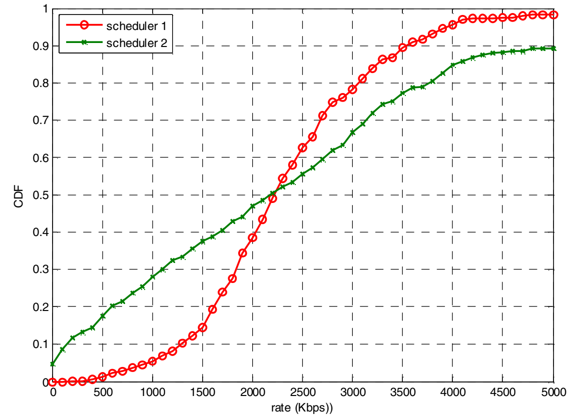

Figure 1: CDF of the user's achieved bit rate