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Joint Time-Frequency Domain Proportional Fair Scheduler with HARQ for 3GPP LTE Systems

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Abstract: This paper explores the potential gain of joint diversity in both frequency domain and time domain which can be exploited to achieve spectral efficiency gains whilst simultaneously facilitating QoS/fairness in an OFDMA system (particularly in 3GPP Long Term Evolution (LTE)). The performance of several joint time-frequency schedulers is investigated. Simulation results show that joint time frequency schedulers achieve significantly superior performance compared to a more conventional time domain (only) proportional fair scheduler. The joint schemes show promising throughput gain while meeting stringent fairness criteria.

I. INTRODUCTION

3GPP LTE will be an all-IP packet based system targeting provision of 100Mbps in the downlink and 50Mbps in the uplink. An improvement of two to four times the spectral efficiency (bits/s/Hz) of 3GPP Release 5 (HSDPA) is also expected. The new standard aims to reduce delays, improve spectrum flexibility and reduce cost for operators and end users [1]. To fulfil these targets, new enabling technologies need to be integrated into the current 3G radio network architectures. Orthogonal Frequency Division Multiple Access (OFDMA) has thus been selected as the downlink access technology for the 3GPP LTE system as it is suitable for high data rate transmission in wideband wireless systems due to its spectral efficiency and good immunity to multipath fading. Moreover, this access technology also provides a possible further enhancement to the system by enabling opportunistic scheduling in the frequency domain. To frequency multiplex users in LTE, subcarriers are divided into sub-channels, and every sub-channel is composed of several neighbouring subcarriers. By grouping the subcarriers into sub-channels, the amount of control signalling and complexity of scheduling can be reduced considerably. Though smaller frequency resolution gives a larger degree of freedom and gain in scheduling, the loss associated with reducing frequency resolution is ameliorated to some degree by the correlation of fading in the frequency domain – grouping sub-carriers within the coherence bandwidth of the channel results in minimal performance loss but may significantly reduce feedback overheads and scheduling complexity.

In this paper, the potential diversity gain of joint time and frequency domain scheduling is exploited. A first layer of scheduling wherein fairness constraints are imposed is implemented in time domain (TD) and is followed by opportunistic scheduling in frequency domain (FD) intended to improve throughput. In the time domain scheduling, the proportional fair (PF) scheduling algorithm is considered, which provides an attractive ability to tradeoff between throughput and fairness. This algorithm is used to schedule a sub-set of users for

the transmission interval under consideration. In the frequency domain, the scheduler aims to optimize the gain of multi-user frequency diversity, within the constraints of the prior TD scheduling of selected users.

Many algorithms for subcarrier allocation in OFDMA systems have been proposed and discussed in the literature to improve the system performance. However, many of them do not jointly consider design issues of a practical system such as retransmission mechanisms, overhead of control signalling, number of multiplexing users and overall system fairness. In this paper, these crucial design issues will be taken into consideration. Various joint time frequency schedulers [2] [3] are investigated, and a low complexity dynamic allocation scheme in the frequency domain is proposed which attempts to both exploit multiuser diversity and facilitate fairness.

The rest of this paper is organized as follows. In Section II, the OFDMA system and channel models will be presented. Packet scheduling algorithms and proposed joint time-frequency schedulers are described in Section III. Simulation results are presented and discussed in Section IV. Section V concludes the paper.

II OFDMA SYSTEM AND CHANNEL MODEL

OFDMA is a multiple access scheme based on OFDM where data is transmitted to different users on different subcarriers. It is a very attractive choice for the LTE as it is suitable for high data rate transmission in wideband wireless systems due to its spectral efficiency and good immunity to multipath fading. The key parameters of the LTE OFDMA downlink system assumed in this paper are given Table 1.

Table 1: Parameters for LTE OFDMA downlink

Transmission BW	10 MHz	
Sub-frame duration	1ms	
Sub-carrier spacing	15kHz	
Sampling frequency	15.36MHz (4x3.84MHz)	
FFT size	1024	
Number of occupied sub-carriers	601	
Number of OFDM symbols per sub frame (Short/Long CP)	7/6	
CP length (µs/samples)	Short	(4.69/72)x6
	Long	(5.21/80)x1
	Long	(16.67/256)

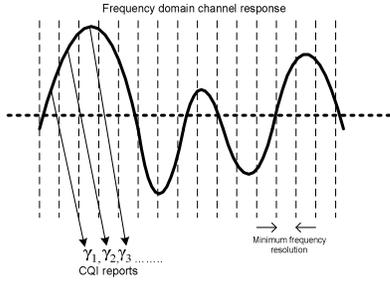


Figure 1: Illustration of CQI Feedback

To frequency multiplex users in the LTE system, the total bandwidth is divided into sub-channels, denoted as physical resource blocks (PRBs). A PRB is the minimum resolution for scheduling in the frequency domain. There are 50 PRBs in a 10MHz system, each consisting of a 12 neighbouring sub-carriers. The sub-carrier bandwidth is 15kHz and the PRB bandwidth is 180kHz. A single Channel quality indicator (CQI) (calculated from the average quality of the 12 sub-carriers) can be fed back for each PRB as shown in figure 1. An example of how subcarriers are grouped and allocated is shown in figure 2.



Figure 2: Illustrations of PRBs groupings

This paper evaluates the performance of scheduling algorithms in a single cell scenario by software simulation. The simulation employs the 3GPP Spatial Channel Model Extension (SCME) as specified in [5]. Inter-cell interference is not considered or included in the additive Gaussian noise. Users are uniformly distributed in the cell and thus experience different SNR, depending on their location in the cell. It is assumed that the measured SNRs of each user are ideally fed back to the BS without any error. Control bits for packet retransmissions are also decoded without errors. Path loss, large scale shadowing fading and temporal fast fading are included in the simulation. SCME defines three environments (Suburban Macro, Urban Macro, and Urban Micro) where the default scenario used in the results presented below is Urban Macro. A new channel impulse response is used at each new packet transmission and remains the same during the transmission of that packet. In order to reduce the computation load for link level simulations, a link-to-system level mapping is used. PER is calculated based on a link level simulation look up table. Random errors are added according to the required PER. Several hybrid automatic retransmission request (HARQ) techniques [4] are under consideration in LTE. In this simulation, HARQ employing Chase Combining is assumed and the maximum number of retransmissions is limited to 4. Figure 3 shows the PER performance with HARQ of various Modulation and Coding Scheme (MCS) levels of LTE in additive white Gaussian noise (AWGN) channels as well as the SCME Urban Macro channel. System simulation parameters and assumptions are summarised in Table 2.

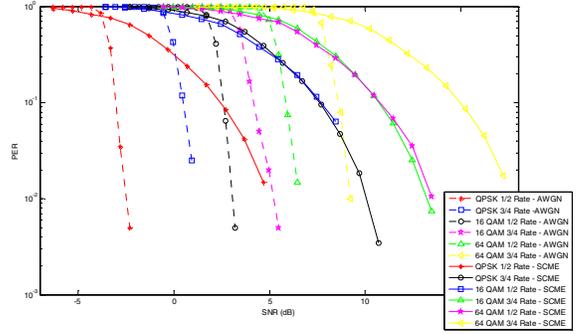


Figure 3: PER performance for various MCS levels in AWGN and SCME channels with HARQ

Table 2: Default System Simulation Parameters and assumptions

Cell Layout	Single Cell
Radius of Cell	500m (min 35 meter)
BS Tx Power	43dBm (20W)
Max. No. of Retransmission	4
Carrier Frequency	2GHz
ARQ Scheme	Chase Combining
Propagation Model	SCM – Urban Macro
Shadowing	SCM – Urban Macro
Noise Power	-104dBm
UE Noise Figure	9dB
Receiver Sensitivity	-95dBm
Packet Arrival	Full Buffer
Number of Time Samples (TTIs)	20000
Average number of user per cell	20
CQI Measurement Error	Ideal
MCS Selection Rule	CQI Measurement
MCS Update Rule	Per frame (1ms)
MCS Level	QPSK 1/2 & 3/4, 16QAM 1/2 & 3/4 and 64QAM 1/2 & 3/4
Link Adaptation Target	10% PER

III. JOINT TIME AND FREQUENCY SCHEDULER

In the joint time frequency scheduler, the first layer of scheduling will be implemented in time domain (TD) and the second layer in the frequency domain (FD). The TD scheduler aims to select users with relatively good channel while maintaining fairness to all users. In combination with this, different FD schedulers with different aims are considered. Figure 4 shows how information is fed into schedulers and interactions between time and frequency domain schedulers.

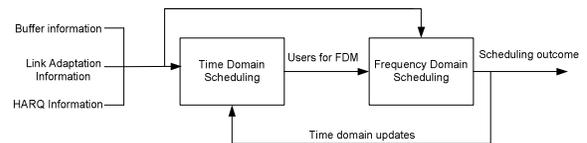


Figure 4: Illustration of Joint Time-Frequency scheduler

A) Time Domain Scheduler

In the time domain, a PF scheduler is considered, which is well known to provide an attractive ability to tradeoff between maximum average throughput and user fairness. The essence of this algorithm is to allocate approximately the same number of resources to all users (averaged over a period of time) and to try to allocate resource in any given scheduling interval to a user whose channel condition is near its peak. Proportional fairness can be achieved by transmitting to a user with highest priority which has the maximum value of:

$$P_k(t) = \frac{R_k(t)}{T_k(t)} \quad \text{at any time slot } t \quad (1)$$

where $R_k(t)$ represents the current requested transmission rate which is normally chosen from a set of available MCS based on the SINR feedback from user. $T_k(t)$ represents the user's average throughput over a window in the past.

The user's average throughput at time t is calculated by:

$$T_k(t) = \begin{cases} (1 - \frac{1}{t_c})T_k(t-1) + \frac{1}{t_c}R_k(t) & \text{if } k \text{ is served at time } t \\ (1 - \frac{1}{t_c})T_k(t-1) & \text{otherwise} \end{cases} \quad (2)$$

where t_c is the window size of the average throughput. In this paper t_c is set to 500. The initial average throughput value for PF ranking will be defaulted to the first reported CQI and will be based on the MCS selected for the user via Link Adaptation (LA).

In the context of OFDMA, a subset of users, the number of which is termed 'multiplexing users' and denoted k , with the highest priorities will be selected for subsequent FD scheduling. The effect of different number of multiplexing users in each time slot or sub frame is investigated in section IV. All users within the cell will be considered, including users with new data as well as users with pending retransmission. Users with retransmission will be prioritized with the fact that their retransmissions will have higher chance of successful transmission due to the gain of Hybrid ARQ. The effective rate for user with pending retransmission is calculated based on:

$$R_{\text{Eff}} = R_{\text{MCS}}(\text{SNR_CC}) \quad (3)$$

where SNR_CC is the accumulated SNR over the retransmissions in Chase Combining.

B) Frequency Domain Scheduler

In order to allocate the resources in frequency domain to the selected users, several well-known scheduling techniques will be investigated. Additionally a sub-optimal but low complexity dynamic allocation strategy is proposed and considered.

- **No Frequency Domain Scheduling (TD-PF)**

Scheduling is only performed in the time domain using the PF algorithm described above.

- **Frequency-Domain Round Robin (FD-RR)**

All PRBs are scheduled with a straightforward method where selected users are serviced in a round-robin fashion. All users must be allocated a PRB before re-allocating to the same user since it is assumed that all users require the same QoS.

- **Frequency-Domain Max C/I (FD-MAX)**

All PRBs are scheduled with a straightforward method where all users are ranked by the order of SNR in each PRB. Users with highest rank in each PRB will be scheduled to transmit.

$$k = \arg \max(\gamma_k(t)) \quad (4)$$

- **Frequency-Domain Proportional Fair (FD-PF)**

For each PRB, PF ranking of selected users is computed by:

$$k = \arg \max \left(\frac{R_{k,j}(t)}{T_k(t)} \right) \quad (5)$$

where $R_{k,j}(t)$ denotes the instantaneous achievable rate at PRB j and $T_k(t)$ represents user's average throughput. The Highest ranked user k will be scheduled to transmit at that PRB j .

Two FD-PF strategies are considered [2]:

- Strategy I: The average throughput $T_k(t)$ is updated for each new time interval (after all PRBs are allocated)
- Strategy II: The average throughput $T_k(t)$ is updated after each PRB is allocated.

- **Frequency domain Dynamic Allocation (FD-DA)**

The proposed algorithm ensures an equal share of PRB among selected users, but not a fair fraction of capacity. However this sub-optimal but low complexity algorithm approximately maximises capacity given the equal resource constraint [6]. In the algorithm, N represents all the PRBs available from 1 to 50 and k represent number of users to be multiplexed in each time slot. The algorithm is as follows:

Initialization

Available PRB, $N = 50$

While available PRB, N are not equal to 0

Loop through multiplexing users, k

User k selects a best PRB from the available PRBs

Remove selected PRB from available PRBs

End user loop

End while loop

IV. SIMULATION RESULTS

In order to obtain diversity gain in the time and frequency domain, sufficient numbers of users must be present. The capacity performance of various schedulers with the increasing number of users in a cell is first investigated. The FD-MAX and FD-RR schedulers mainly serve as reference schedulers. However, in order to quantify the performance gain of additional opportunistic scheduling in frequency domain, the TD PF scheduler is also considered. From Figure 5, it can be seen that the joint time-frequency PF schedulers, FD-PF-I and FD-PF-II achieve near identical performance which is significantly superior to TD-PF. With increasing number of users, more diversity gains could be exploited and thus the performance gain increases. In the case of equal resource allocation, the proposed scheduler significantly outperforms FD-RR. The FD-DA scheduler also achieves higher throughput than TD-PF when there are a sufficient number of users in the cell, e.g. more than 17 users. The slight oscillatory nature of this performance curve can be attributed to the ability to allocate extra resource to strong users when the number of PRBs slightly exceeds an integer multiple of the number of users. The FD-MAX scheduler clearly offers the best performance in terms of capacity but is not expected to achieve good performance in terms of fairness.

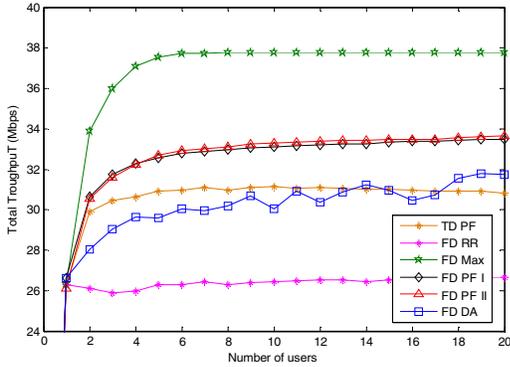


Figure 5: Throughput performance with increasing number of users in a cell

For the results in Figure 5, the number of possible multiplexing users per time slot is fixed and equal to the number of users in the cell. However, not all users are actually scheduled per time slot due to the nature of some schedulers. Figure 6 shows the number actually scheduled. For round robin and dynamic allocation methods, the number of scheduled users always equals the number of multiplexing users as these algorithms ensure an equal share of resource among all users. The Max C/I algorithm favours only users with high SNR, which are location dependent. In the case of FD-PF, the average number of scheduled users for strategy II is much higher than strategy I. This is due to the fact that in strategy I, there is no instantaneous update to the average throughput after each PRB and thus users with lower PF ranking priorities will not be selected.

If all the multiplexing users are scheduled in the frequency domain, multi-user diversity might well be maximized but the

inherent multi-user diversity in the time domain is not being utilized, especially in the case of the equal resource allocation algorithms. Figure 7 shows how the FD-PF-I, FD-PF-II and FD-DA schedulers perform with increasing number of possible multiplexing users in each time slot. These schedulers all benefit from increasing number of multiplexing users in each time slot due to opportunistic scheduling in frequency domain. However the gain saturates when approximately 70% of all users are multiplexed and the gain diminishes when more users are multiplexed. This is simply due to the fact that resources are allocated to all users including those in deep fades and thus achieving poor performance. It can then be concluded from these results that to balance the diversity gain from both time and frequency domain, approximately 50-70% of all users should be selected as possible multiplexing users to transmit in each time instance in order to achieve a good trade-off. In particular, FD-DA significantly outperformed both FD-PF schedulers in this range. FD-DA performance degrades more rapidly once the number of possible multiplexing users increases beyond this range due to the constraint to allocate resource to all possible multiplexing users.

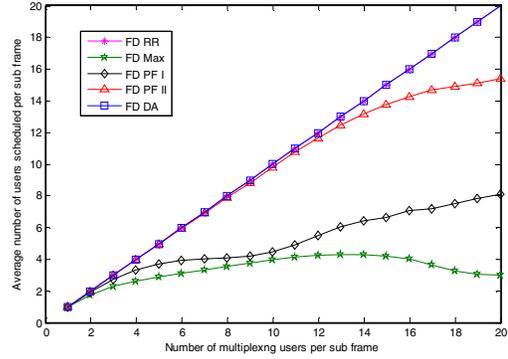


Figure 6: Number of multiplexing users vs. scheduled users

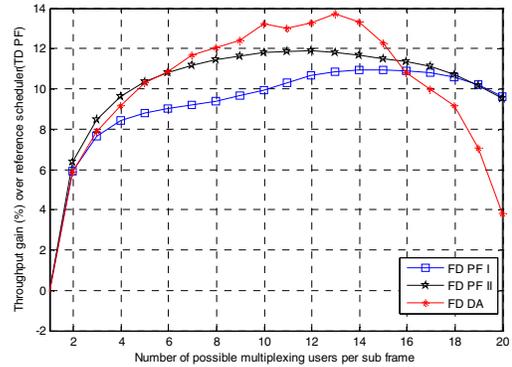


Figure 7: Performance gain of proposed schedulers with increasing number of possible multiplexing users in a sub frame

Throughput performance with the number of possible multiplexing users equal to 50% of all users is then considered in Figure 8 (with performance also shown for the 100% case as a reference). It can be seen that FD-DA outperforms all other

schemes except TD-MAX when there are a sufficient number of users in a cell, e.g. 6 or more. This is clearly a likely scenario. It can also be seen that the FD-PF strategies are much less sensitive than FD-DA to the number of multiplexing users.

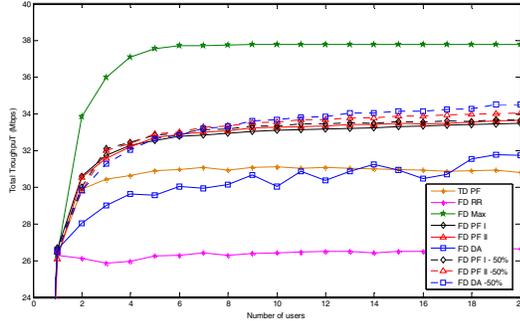


Figure 8: Throughput performance with 50% users selected of all multiplexing users

Often, gain in throughput is achieved through some kind of compromise in fairness and vice versa. Therefore considerable attention has been given to investigating the fairness performance of the proposed schedulers. It is well known that a proportionally fair scheduler should maximize the sum of logarithmic average user rates [7].

In the context of this paper, a fairness metric is employed based on [8]:

$$Fairness_Metric(i) = \left(\prod_{n=1}^k R_{inst}(i) \right)^{\frac{1}{k}} \quad (6)$$

Based on the previous results, selecting 10 (50%) multiplexing users for FD scheduling in each time slot achieves promising results, in a cell of 20 users. Figure 9 shows the fairness performance of various schedulers with a fixed value of 10 multiplexing users in each time slot in the form of the cdf of the fairness metric achieved. FD-MAX, optimal in throughput terms, performs badly in terms of fairness as expected. FD-RR and TD-PF achieve better fairness than FD-MAX. By exploiting the diversity in the time and frequency domain, it is possible to allocate resource more fairly to all users. Hence, both FD-PF strategies achieve better fairness than the TD-PF scheduler, with FD-PF-II superior due to its more frequent update of $T_k(t)$. FD-DA, which attempts to maximise throughput in the frequency domain, but maintains an element of fairness by allocating equal resources, also performs well, achieving fairness better than TD-PF and FD-PF-I and similar to FD-PF-II.

V. CONCLUSION

In this paper, the potential gain achievable through scheduling jointly in both frequency domain and time domain to exploit both domains of diversity has been investigated for an LTE OFDMA system employing HARQ. Simulation results have shown that joint time frequency proportional fair schedulers achieve significant improvements in performance compared to a frequency-blind, time-domain-only proportional fair scheduler. For the scenario considered in this paper, in order to balance the

diversity gain from both time and frequency domain, approximately 50-70% of all multiplexing users should be selected to transmit in each time slot to gain the best exploitation of diversity available in the time and frequency domains. Further investigation is required in order to determine if this criteria is true for other scenarios. Two variants of a combination of proportional fair scheduling in time and frequency domains achieve good performance in terms of both throughput and fairness. A combination of time domain proportional fair and frequency domain dynamic allocation, achieves similar fairness and superior throughput.

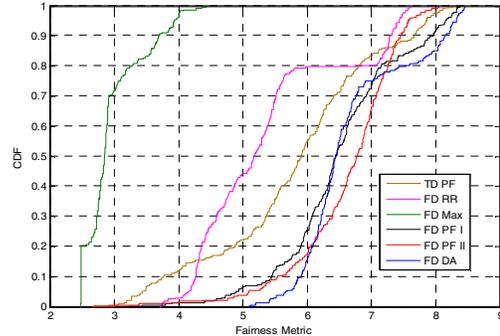


Figure 9: Performance comparison of proposed schedulers with 10 multiplexing users in a sub frame, in a cell with 20 active users

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