Performance Evaluation of Cross-Layer Scheduling Algorithms over MIMO-OFDM

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Abstract*—In this paper, we present a performance evaluation for six scheduling algorithms over a MIMO-OFDM based cellular system. We have selected a set of scheduling algorithms that may use information about the instantaneous channel conditions, status of transmission queues, QoS requirements or pending HARQ retransmissions. Performance evaluation is focused on average delay under different cell load conditions, which indirectly provides information on the capacity gain associated to each algorithm. Simulation results show that channel aware algorithms (like M-LWDF) jointly used with a MU-MIMO multiplexing transmission mode obtain the best performance in terms of spectral efficiency.

Scheduling, Diversity, MIMO, OFDM, Multiuser

I. INTRODUCTION

The evolution of mobile communication networks is characterized by an increasing demand of services and applications. Emergent radio access technologies are targeted to increase data rates as well as to provide higher service reliability.

A wide set of physical layer techniques have been defined in cellular standardization bodies to enhance the radio capabilities. For instance, Adaptive Modulation and Coding (AMC) is responsible for maximizing the data rate while keeping a desired target Bit Error Rate (BER_T). The use of Orthogonal Frequency Division Multiple Access (OFDMA) has allowed increasing the spectral efficiency by exploiting the frequency domain diversity. Multiple antenna technologies (MIMO) are also defined to improve the radio performance in terms of coverage, QoS, and targeted data rates. All these features are integrated as part of the radio interface specifications in technologies like WiMAX or Long Term Evolution (LTE).

The key feature to manage the scarce radio resources and provide Quality of Service (QoS) is the L1/L2 scheduling algorithm. The goal of the scheduling is to distribute the available radio resources in the cell among the user terminals according to a particular policy. Such policy must take into account varying radio channel conditions (both in time and frequency) in order to maximize the spectral efficiency by allocating the channel to those users experiencing the highest Signal to Noise Ratio (SNR). It takes advantage of the uncorrelated channels between users due to their different locations, which in practice results in different potential throughput along the time and frequency resources.

When the scheduling is used in conjunction with AMC, OFDMA and MIMO, more degrees of freedom are available in time, frequency and space domains. Thus, the scheduler can take advantage of the instantaneous variation of the SNR along the time, in the different frequency bands and between the different spatial channels.

Scheduling algorithms have been typically designed just to maximize the spectral efficiency. However, it presents the difficulty of ensuring fairness and QoS, so there exist many other implementations in the group of “Fair Scheduling” that pays more attention to latency for each user than to the total achieved data rate. This is particularly important for real-time applications such as Voice-over-IP (VoIP) or video-conferencing, where a certain minimum rate must be guaranteed independently of the channel state. Hence, there are many possible implementations depending on the specific target to be achieved: maximizing the spectral efficiency, minimizing the delay, providing fairness between users, etc.

In this paper, we evaluate a set of cross-layer scheduling algorithms over a MIMO-OFDM based cellular system. We have selected a wide set of scheduling algorithms that may use (or not) information about the instantaneous channel conditions, status of transmission queues, QoS requirements or pending HARQ retransmissions. Scheduling algorithms have been tested over different MIMO transmission modes. Performance evaluation is focused on average delay under different cell load conditions, which indirectly provides information on the capacity gain associated to each algorithm. Results in this work are shown for an MIMO-OFDMA scheme similar to that in 3GPP-LTE [5].

The remainder of this paper is organized as follows. The system model is outlined in section II. The scheduling algorithms evaluated in this paper are described in section III. Section IV presents the simulation results. Finally, section V states the main conclusions of this work.

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II. SYSTEM MODEL

The system model evaluated in this paper is shown in Figure 1. A video streaming model represents the generation of data by the user. Using a Truncated Pareto distribution, each user generates both a variable number of bits (loaded into a separate queue) and the inter-arrival time between packets, whose instantaneous rate is given by $S_i[n]$ for user i at instant n. The size of the queues is limited and therefore there might be overflow. Those packets which can not be queued are counted as queue losses. Within a specific queue, bits are served on a First In First Out (FIFO) basis. Delay measurements $W_i[n]$ correspond to the waiting time in the queue experienced by the last packet served, that is, the head of line packet [1].

The MIMO transmitter uses either transmit diversity or spatial multiplexing modes to increase the instantaneous SNR or data rates for a given transmission reliability, respectively. Both the transmitter and the receiver use M antennas. On the one hand, transmit diversity allows only to send one independent data flow from all the antennas, whereas up to M independent data flows can be simultaneously transmitted using spatial multiplexing.

The MIMO channel is Rayleigh fading frequency selective (including the effects of delayed taps due to multipath). Moreover, Additive White Gaussian Noise (AWGN) is added at the receiver. Each path between two antennas (transmitter and receiver) is a SISO (Single Input Single Output) broadband channel. The MIMO channel includes the effect of spatial antenna correlation assuming the well-known Kronecker correlation structure; the MIMO channel $\mathbf{H}$ is a matrix of MxM time varying channels with certain correlation characterized by the parameter ρ (see [1] for more details).

A set of N_u users share the radio resources. Although the receiving process is not the scope of this work, the implemented receiver is Zero Forcing, that is, M orthogonal paths are obtained by inverting the matrix channel [1]. The scheduling algorithm is in charge of assigning the transmission turns to the N_u users that share the physical resources.

In LTE technology, radio resources are structured in slots of length T_{slot} = 0.5 ms. The Transmission Time Interval (TTI) is set to 1 ms, thus containing 2 slots. Each slot can be seen as a time-frequency resource grid composed by OFDM symbols along the time. Each slot is divided into a number of Physical Resource Blocks (PRBs) consisting of 12 consecutive sub-carriers along 7 consecutive OFDM symbols. Assuming a system bandwidth BW = 5 MHz, there is a total of 300 data subcarriers per OFDM symbol, so the number of PRBs is 300/12 = 25. This number will be hereinafter considered as the number of "channels" $N_c = 25$.

LTE downlink scheduling is carried out in a subframe basis. The minimum allocable unit to a user is formed by two consecutive PRBs along the time, as shown in Figure 2.

The received instantaneous SNR at subframe n for user i, PRB k and stream m, $\gamma_{ikm}[n]$, determines the achievable throughput (in bits) $r_{ikm}[n]$. Certain constellation switching thresholds are determined by the target Bit Error Rate (BER_T).

Scheduling criteria are here based on the channel states $\gamma_{ikm}[n]$, QoS information and/or the waiting time in the queues $W_i[n]$. Knowledge of the channel state matrix is assumed to be perfect, i.e. it is available at the multiplexer without any error or delay.

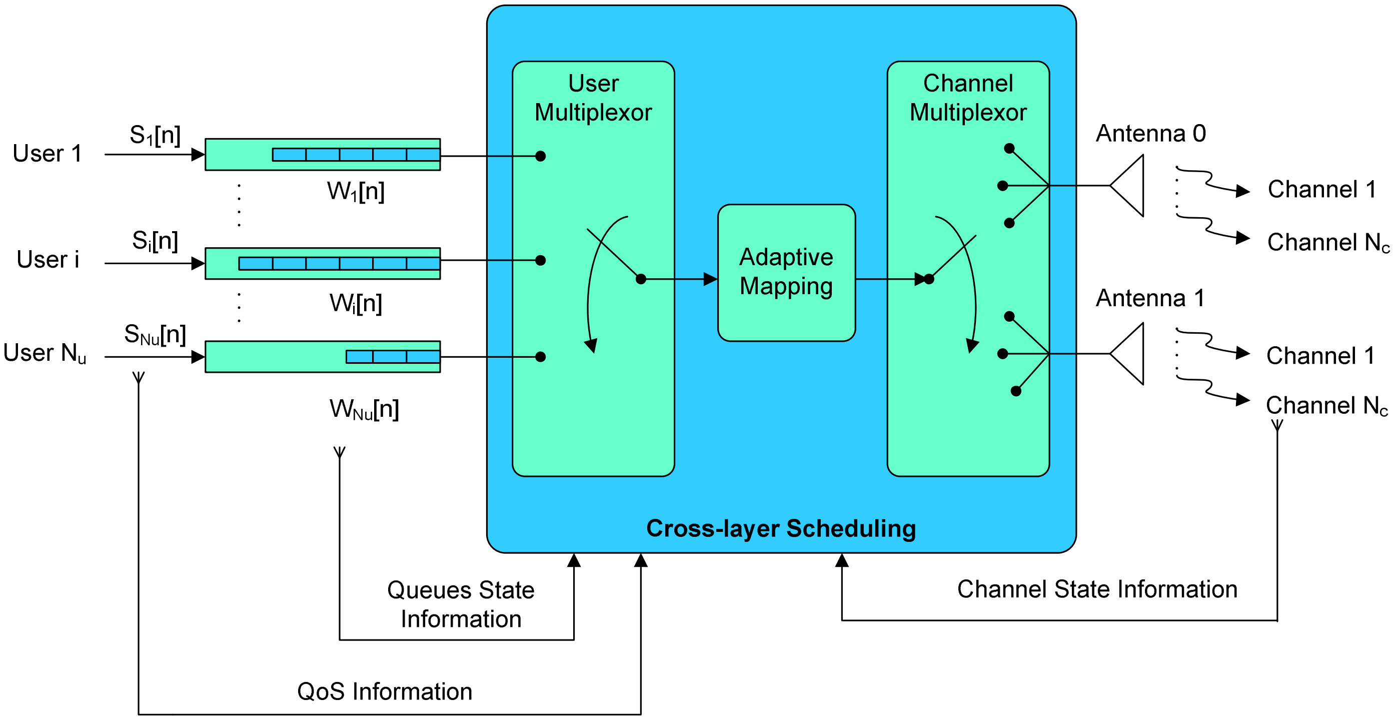


Figure 1. System model (transmitter) with M=2 antennas

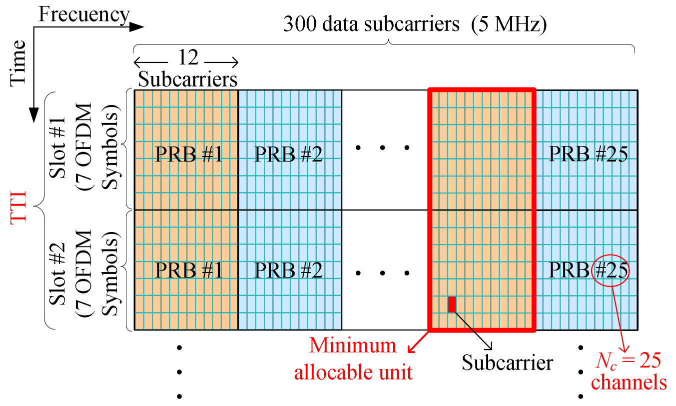


Figure 2. LTE physical resources structure

III. SCHEDULING ALGORITHMS

Six different scheduling algorithms have been evaluated in this paper:

- *Round Robin* (RR) is fair among users as long as data sources are similar, although it can get no multiuser or multichannel diversity gain.
- *Best Channel* (BC) assigns the radio resources to the users with the highest potential rate $r_{ikm}[n]$. BC will get the highest throughput for some users but at the expense of some others' starvation.
- *Proportional Fair Scheduling* (PFS) [4] schedules a user when its instantaneous channel quality is high compared to its own average channel condition over time. This scheduler maximizes average throughput in a long term scale. Multiuser diversity benefit can still be extracted because channels of different users fluctuate independently so that if there is a sufficient number of users in the system, there will likely be a user near its peak at any time [5].
- *Largest Delay First* (LDF) [6] is adaptive to the delay, providing the transmission turn to the user who has experienced the highest waiting time $W_i[n]$.
- *Modified Largest Weighted Delay First* (M-LWDF) [7] considers both the channel quality and QoS indicators in its scheduling criteria by allocating the resources to the user with higher potential rate and delay product. According to [7], M-LWDF algorithm is throughput-wise optimal as it gets the maximum possible diversity gain.
- *Exponential Rule* (ER) is based on a two-factor equation [6], being the first term dominant as long as delays do not grow too large from the average. Otherwise, the exponential factor will give priority to the user with largest delay.

IV. SIMULATION RESULTS

In this section, the performance of six scheduling algorithms over different MIMO-OFDM techniques in LTE downlink scenario is compared in terms of mean packet delay, which is an indirect measurement of the capacity gain achieved by the algorithms.

Four MIMO-OFDM techniques are presented in this paper. Two of them are *transmit diversity* techniques, such as Space Frequency Block Code (SFBC) and Beamforming (BF). The other two techniques, based on *spatial multiplexing*, are: MIMO Multiplexing without precoding and Multiplexing with precoding. Ideal precoding based on singular value decomposition (SVD) of the channel matrix is employed for BF and Multiplexing with precoding techniques [2].

In addition, multiplexing without precoding supports Multi-User MIMO (MU-MIMO) scheme, that is, multiple users in same radio (frequency-time) resource can be allocated together. The rest of techniques work with Single-User MIMO (SU-MIMO) scheme, so that only one user can be allocated in one frequency-time resource.

We use the MIMO 2x2 basic antenna configuration according to 3GPP-LTE [3], that is, 2 antennas at the transmitter and 2 antennas at the receiver. The number of users is kept fixed and each user generates data at the same average rate. However, from one simulation to another, this rate is increased in short steps by increasing the mean packet size in the Truncated Pareto distribution. The maximum packet size is fixed to the double of the mean. All users have the same channel conditions and no QoS requirements. The rest of the simulation parameters are summarized in Table I.

TABLE I. SIMULATION PARAMETER VALUES

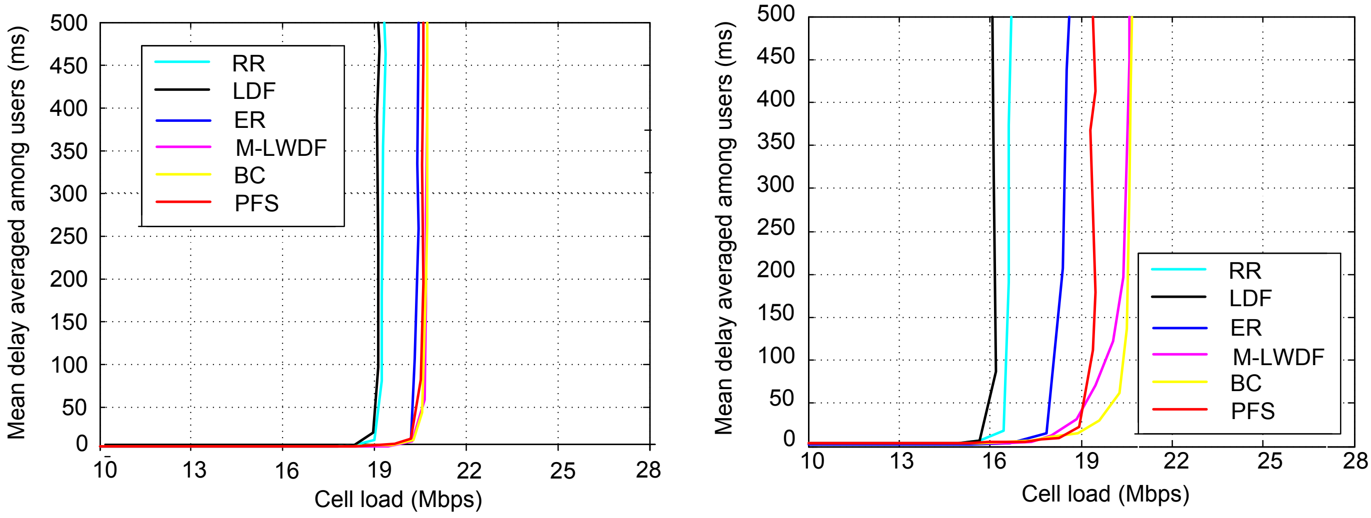
Parameter	**Value**
Number of users	10
FFT size	512
Data subcarriers	300
Sampling frequency	7.68 MHz
Carrier frequency	2.5 GHz
Average SNR	20 dB
Terminal speed	4 km/h
Target BER	10^{-3}
Simulation length	10 s
TTI	1 ms
Bandwidth	5 MHz
PRBs per subframe	25
Modulations	QPSK,16QAM,64QAM

The achievable system capacity is evaluated by analyzing the mean packet delay averaged among users. Delay goes towards infinity when queues become unstable, that is, for the maximum attainable capacity. The attainable capacity depends on both the MIMO transmission technique and the scheduling algorithm.

Figure 3 a) and b) present simulation results for transmit diversity techniques. Round Robin (RR) and Largest Delay First (LDF) are scheduling algorithms which offer low system capacity. RR is a fixed algorithm whereas LDF is adaptive to the delay, so neither of them is channel-aware therefore they do not provide any diversity gain. Exponential Rule (ER), Modified Largest Weight Delay First (M-LWDF), Best Channel (BC) and Proportional Fair Scheduling (PFS) are opportunistic algorithms. They present multiuser and multichannel diversity gain. BC offers the maximum diversity gain and hence maximum capacity, while M-LWDF, ER and PFS offer diversity gain that is determined by delay and QoS conditions. Simulation results show that PFS performs better capacity than ER, whereas M-LWDF outperforms PFS.

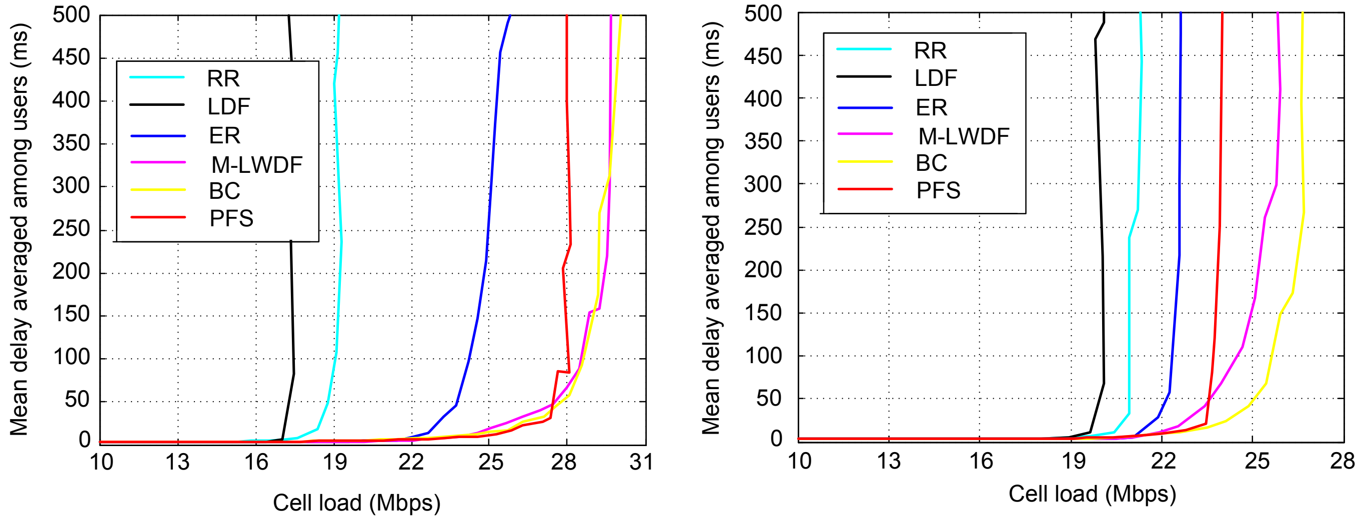
SFBC results show a gap of approximately 4 Mbps between LDF (that is a non channel aware algorithm) and BC or M-LWDF, which are channel-aware algorithms. Regarding Beamforming results, non opportunistic algorithms like LDF and RR reach a throughput of 19 Mbps instead of 16 Mbps as it happens in SFBC results. This is due to precoding, which leads to an improvement of the effective SNR. Additionally, the gap between these algorithms and the rest is reduced to 1 Mbps. There is no significant difference among BC, M-LWDF, PFS and ER related to efficiency.

Spatial multiplexing results are shown in Figure 3 c) and d). The fixed (RR) and delay adaptive (LDF) schedulers achieve better results when precoding is applied. When precoding is not applied, simulation results show that the system capacity is spread roughly from 17 Mbps to 28 Mbps for LDF and BC respectively. On the other hand, when precoding is used, results are gathered from approximately 20 Mbps to 26 Mbps for the worst and best performance algorithm, respectively.



a) Beamforming

b) SFBC



c) Multiplexing without precoding

d) Multiplexing with precoding (SVD)

Figure 3. Performance evaluation of scheduling algorithm for different MIMO transmission modes

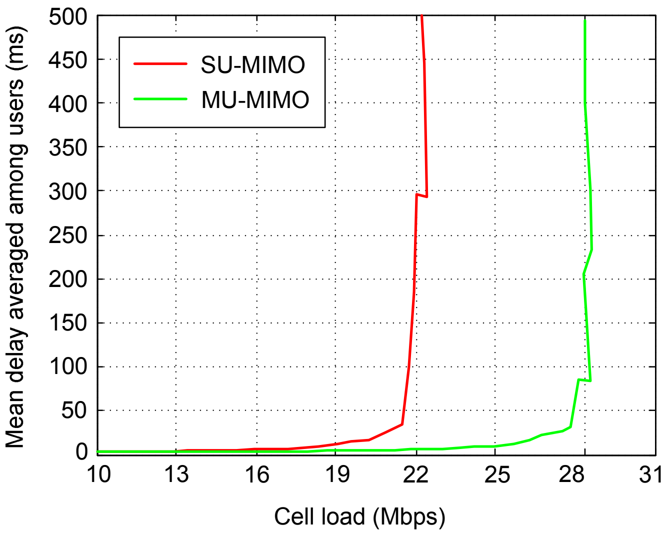


Figure 4. SU-MIMO vs MU-MIMO

Figure 4 shows the difference of attainable throughput between SU-MIMO and MU-MIMO schemes for PFS (an opportunistic algorithm) when using a MIMO Multiplexing without precoding scheme. Simulation results show that MU-MIMO scheme performs better than SU-MIMO in terms of throughput. This is due to the fact that MU-MIMO assigns resource blocks to each stream independently, that is, the user experiencing the best instantaneous channel conditions is allocated in each stream. On the other hand, SU-MIMO scheme allocates both streams to the user with the highest aggregated attainable throughput.

V. CONCLUSIONS

In this paper, we have presented a performance evaluation of six scheduling algorithms over different MIMO-OFDM schemes.

In terms of spectral efficiency, simulation results show that channel-aware algorithms obtain the best performance. Besides, it has been proved that spatial multiplexing techniques provides the highest throughput under these simulation conditions, such as low terminal speed and high SNR. To sum up, the highest capacity gain is achieved for BC and M-LWDF algorithms over a MIMO Multiplexing transmission mode, although BC is well known for being an unfair algorithm (results not shown in this paper).

Finally, simulation results show that MU-MIMO scheme outperforms the SU-MIMO one when opportunistic algorithms are applied.

ACKNOWLEDGMENT

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