Pre-Processing Effects for Limited CSI Feedback in Scheduling Algorithms Using Cross-Layer Issues

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Abstract— In this paper we introduce a new Pre-Processing Method (PPM) and we observe its impact in scheduling algorithms. We also suggest a Cumulative Distribution Function (CDF) curve of Signal-to-Noise Ratio (SNR) of the scheduled users. This CDF curve reflects characteristics of application and information about scheduling policies. Based on these curves, thresholds are defined in order to avoid reporting of unnecessary Channel State Information (CSI). This saving of resources is very important when dealing with limited feedback that may limit the system performance/capacity. Simulation results confirm the potential of the proposal.

Keywords— scheduling policies, physical layer, cross-layer, channel state information.

I. INTRODUCTION

The Open Systems Interconnection (OSI) protocol model is a well-accepted framework for communication systems which are decomposed into seven protocol layers (physical-link-network-transport-session-presentation-application) and each one is responsible for a subset of the system operation functions. Each protocol layer communicates only with the layers directly above or below it. Thus, they are usually evolved independently and considerable research efforts have been done for improving the efficiency of individual protocol layers [1], [2].

Future Fourth Generation (4G) networks must support high data rates applications with heterogeneous and variable Quality of Service (QoS) parameters and demand a high flexibility of involved protocol layers. Cross-layer design [3] refers to protocol design done by actively exploiting the dependence between protocol layers to obtain performance gains. This is unlike with OSI protocol model, where each layer is designed independently from another. Several publications have investigated the benefits in systems with cross-layer policies [1], [2], [8], [9]. A very common problem to be solved, in wireless systems, is predict the radio channel and combat wireless link impairments [6]. Physical layer (PHY) continuously generates detailed information about the current radio channel conditions, that we called it by Channel State Information (CSI). Therefore, CSI can be used to solve this explained problem.

Orthogonal Frequency Division Multiplexing (OFDM) transmission technique has gained a lot of attention in part

due to its facilities to inform the CSI from the mobile station to the base station. OFDM is an evolved form of multicarrier transmission where a single high-speed data stream is transmitted over a number of lower-rate subcarriers [5]. OFDM also has a number of unique features that makes it an attractive choice such as robustness against multipath fading and intersymbol interference.

Besides these OFDM advantages, we can observe a new problem: the greater is the number of subcarriers, the greater is the correspondent feedback required. However, a very common issue in the upcoming wireless systems is the ability of working with a very limited amount of feedback information. This is a very limiting aspect of the system and is a growing research topic nowadays.

Cross-layer optimization can be performed in a number of ways. The choice of the involved layers and the metric are key aspects on such task. In our case, we aim to observe the joint optimization on the PHY and Medium Access Control (MAC) layers. Then, the scheduling problem is a well-adapted scenario for the choice of the most suitable parameters for PHY and MAC jointly. In this paper, we have simulated some system-level interactions to obtain a Cumulative Distribution Function (CDF) curve from Signal-to-Noise Ratio (SNR) values owned by scheduled users. This curve is used as a cross-layer issue in order to avoid the unnecessary feedback. We propose a new Pre-Processing Method (PPM) to help at the selection of SNR to be reported.

The rest of the paper is organized as follows. We use a single-cell system model that will be explained in further details in Section II. Section III is devoted to describe the main characteristics of the used scheduling algorithms. Then, the proposal method will be presented in Section IV. The quantitative results for the applied PPM are presented and compared in Section V. Finally, Section VI summarizes the main obtained goals with some conclusive remarks.

II. SYSTEM ARCHITECTURE

We assume a single-cell system where one base station can transmit to I mobile users. As an Orthogonal Frequency Multiple Access (OFDMA) system, the cell sprectum W is splitted into a set of N subcarriers. The number of subcarriers (N) is chosen sufficiently large to permit that each subcarrier can be seen as an individual flat fading channel. Thus, subcarriers are modeled as N flat Rayleigh fading channels with correlation in time and frequency domains.

A number of L OFDM symbols were simulated. In order to constrain the problem, in each OFDM symbol, it is assumed

that each subcarrier would be assigned only to one user. Each user is modeled with full data buffer using Non-Real Time (NRT) services with different data rate requirements. Each i-th mobile user has knowledge of his own complex channel gain $H_i(n)$ on the n-th subcarrier and can transmit, instantaneously, its CSI to the base station. The SNR per subcarrier $\rho_i(n)$ is defined as [8]:

$$\rho_i(n) = \frac{|H_i(n)|^2 \cdot p}{\eta_i(n)}, \qquad (1)$$

where p is the subcarrier transmit power, which is considered to be equal in all N subcarriers and $\eta_i(n)$ represents the Additive White Gaussian Noise (AWGN) power density function of user i. The SNR $\rho_i(n)$ is used as a quality measure and it is reported to the base station to perform the resource allocation algorithms, such as subcarrier allocation and adaptive modulation.

The possible transmit data rate $c_i(n)$ of the i-th user at the n-th subcarrier is given by [9]

$$c_i(n) = w \cdot \log_2 \left[1 + \beta \rho_i(n) \right], \qquad (2)$$

where w is the subcarrier bandwidth and β is the SNR gap for the system Bit Error Rate (BER) requirements defined as [9]

$$\beta = -\frac{1.5}{\ln(5 \cdot \text{BER})}. \qquad (3)$$

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In order to use finite modulation schemes, a variable M-ary Quadrature Amplitude Modulation (QAM) with modulation levels $M = 2^m$ ($m = 1, 2, 3, 4, 5$ and 6) is employed. In Figure 1, we can observe that the link adaptation scheme is composed of steps, which represent transitions between data rates. Each transition SNR value is called M-QAM SNR threshold, $\rho_{M-\text{QAM}_{th}}$, and its correspondent available data rates, $c_{M-\text{QAM}_{th}}$. For matching the possible transmit data rates to the available data rates, it is done a comparison between the user SNR per subcarrier $\rho_i(n)$, and the M-QAM SNR threshold $\rho_{M-\text{QAM}_{th}}$, as it showed in the Algorithm 1.

Algorithm 1 Pseudo-Code of the comparison between SNR values

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  if $\rho_i(n) < \rho_{2-\text{QAM}_{th}}$ **then**
    $c_i(n) = 0$ **(no transmission)**
  end if
  if $\rho_i(n) > \rho_{64-\text{QAM}_{th}}$ **then**
    $c_i(n) = c_{64-\text{QAM}_{th}}$
  end if
  if $\rho_{M-\text{QAM}_{th}} \leq \rho_i(n) \leq \rho_{(M+1)-\text{QAM}_{th}}$ **then**
    $c_i(n) = c_{M-\text{QAM}_{th}}$
  end if

Let $\mathbf{X}$ indicates the binary assignment matrix which elements $x_i(n)$ are defined as

$$x_i(n) = \begin{cases} 1, & \text{if subcarrier } n \text{ is assigned to user } i \\ 0, & \text{otherwise.} \end{cases} \qquad (4)$$

Hence, r_i is the data rate of user i, defined as:

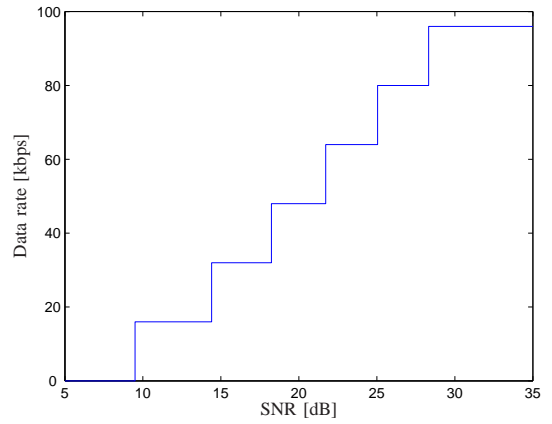$$r_i(\mathbf{X}) = \sum_{n=1}^{N} c_i(n) \cdot x_i(n). \qquad (5)$$

Fig. 1. Link adaptation scheme.

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III. SCHEDULING ALGORITHMS

In this work, we compare the performance of two traditional algorithms, namely the Round Robin (RR) and Rate Adaptive (RA), with and without the influence of the proposed PPM.

Firstly, we present the objectives of each algorithm and, then, we show the proposed method. RR and RA algorithms are not very sensitive to user channel variations and this common characteristic leads to the successful results to be shown in next sections.

A. Round Robin Algorithm

RR algorithm is developed as a cyclic queue of users. Each i-th user is sequentially and periodically scheduled to transmit in all subcarriers of one OFDM symbol, ignoring his channel state information. This algorithm is very simple to be implemented, nevertheless, it guarantees a fair resource management among all users. Fairness is his great advantage, but users with different QoS requirements could be place in disadvantage.

B. Rate Adaptive Algorithm

The RA algorithm concept is to maximize the lower bound of all users, i.e., the lowest mobile user data rate is maximized. The problem goal is defined as:

$$\max_{\mathbf{X}} \quad \epsilon, \quad \text{subject to} \quad r_i(\mathbf{X}) \geq \epsilon \quad \forall i. \qquad (6)$$

In this work, we implemented the Rhee's suboptimal solution [7]. This algorithm aims to guarantee a minimum data rate for the worst-case user. It gives a sort of fairness if data rates of the users are such as quite similar. However, it is unfair in other several cases.

IV. PROPOSED METHOD

We propose a PPM to be executed at the mobile user entity, before it sends his channel state information to the base station. In order to decrease the amount of channel state information reported, the proposed method suggests the user to known the used algorithm characteristics to foresee the possibilities of being scheduled in the next OFDM symbol.

We evaluate the performance of different users with different rate requirements by means of system-level simulations. Several channel realizations per user have been carried out and, the moment that each user was scheduled, his SNR was stored. In the next step, the CDF $F_{\rho_i(sch)}(\cdot)$ of SNR values from scheduled subcarriers of the i-th user was calculated by the following:

$$\rho_i(sch) \longrightarrow F_{\rho_i(sch)}(\rho_i(sch))$$
$$F_{\rho_i(sch)}(\rho_i(sch)) = Pr(\varrho \leq \rho_i(sch)), \quad \forall \rho_i(sch),$$

where $\rho_i(sch)$ are the SNR values of the scheduled subcarriers of the i-th user and ϱ is a random variable.

Six users were simulated with RR algorithm, the equivalent CDF curves for this algorithm are shown in Figure 2. In the same way, six users were simulated with RA algorithm and the equivalent CDF curves for this algorithm are shown in Figure 3.

Depending on the used algorithm, the CDF curve inherently reveals the QoS characteristics, which is the case of RA algorithm that takes into account the data rate requirements. Moreover, the CDF curve gives some information about scheduling policies. Physical layer could then use this additional information on making its proper decisions, as a cross-layer approach.
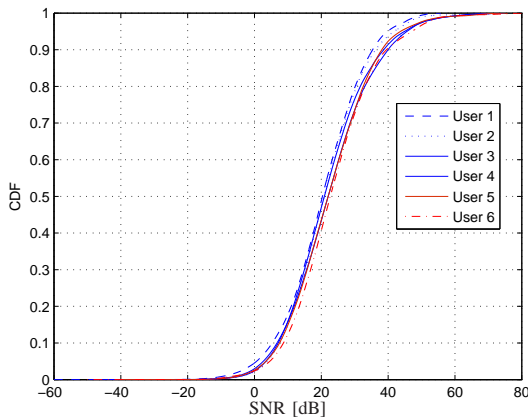

Fig. 2.   Typical CDF for Round Robin algorithm with 6 users

Thinking in this way, the main goal of PPM is to identify a threshold, $F_{i,th}$, where all SNR cumulative probabilities are greater than it, as depicted below:

$$\rho_i(n) \longrightarrow F_{\rho_i(sch)}(\rho_i(n))$$
$$F_{i,th} = F_{\rho_i(sch)}(\rho_{i,th}(n)) = Pr(\varrho \leq \rho_{i,th}(n))$$
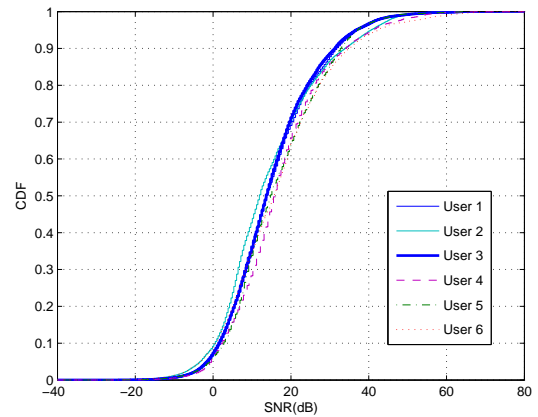$$F_{\rho_i(sch)}(\rho_i(n)) > F_{i,th}, \quad \forall \rho_i(n),$$

Fig. 3.   Typical CDF for Rate Adaptive algorithm with 6 users

where $\rho_{i,th}(n)$ is the established SNR threshold the i-th user.

After this step, mobile users could only have reported subcarrier channel gains whose correspondent SNR values are greater than $\rho_{i,th}(n)$. For the non-reported subcarrier channel gains, mobile users turn off the signalling transmission of these subcarriers, but in case of this work, just for implementation's reasons, pre-stablished dummy bits are transmitted and represented by the element **-inf**.

At the base station, RA algorithm identifies, firstly, subcarrier channel gains per user equal to dummy bits, then the equivalent subcarriers data rates are signalled equal to 0 (no transmission).

The scheduling process is done with user subcarriers whose SNR values are greater than $\rho_{i,th}(n)$. For instance, only the users whose SNR values are greater than this threshold $\rho_{i,th}(n)$ for a specific subcarrier n are considered for the allocation of this subcarrier n.

In the RR algorithm case, firstly, the user is scheduled, then, user subcarrier channel gains equal to dummy bits are identified, and finally, the equivalent subcarriers are signalled with data rate equal to 0 (no transmission). It means that user subcarriers, whose SNR values are greater than $\rho_{i,th}(n)$, are included in the scheduling process. This fact is due to the RR algorithm concept restriction where all subcarriers must be signalled to the user, independent of his subcarrier channel gains.

We must keep in mind that PPM is a powerful method to avoid reporting unnecessary information, but a high $F_{i,th}$ has different impacts depending on the used scheduling algorithm. We can deduce, from the RA algorithm description in Section III-B, that as the $F_{i,th}$ increases, the average system data rate increases also and the priority of users experiencing bad channel conditions decreases. Thus, the PPM method could bring about system data rates improvements. A similar analysis could be done with the the RR algorithm description in Section III-A, where we can deduce that the system data rate stays the same or gets worse.

Therefore, the $F_{i,th}$ definition is an important trade-off to be evaluate in the physical and system level simulations. In addition, as we can see in Figures 2 and 3, a fixed

$F_{i,th}$ corresponds to a distinct SNR region for the scheduling algorithms.

V. SIMULATIONS RESULTS AND DISCUSSIONS

In this section, we describe the simulation scenario to be used for performance evaluation. The basic wireless system simulation parameters are listed in Table I.

TABLE I

BASIC SIMULATION PARAMETERS.

Parameter	Value
System frequency	2 GHz
Number of subcarriers	150
Subcarrier bandwidth	15 KHz
Cell format	circular
Maximum distance from base station	1 Km
Minimum distance from base station	10 m
Shadowing standard deviation	8 dB
OFDM symbol period	62,5 μs
Total system power	20 W

It was used a *MATLAB* program developed by Wireless Telecommunication Research Group, where we assumed a single-cell system model with one base-station and six users with different data rate requirements, as presented in Table II. We have simulated 200 channel realizations in the simulation campaign. Each channel realization has a number of 2400 OFDM symbols. For implementation's reasons, used algorithms schedule a sub-frame with 8 OFDM symbols, i.e., the transmission has the same scheduling configuration on the whole sub-frame.

TABLE II

DATA RATE PARAMETERS FOR PERFORMANCE EVALUATION:

Parameter	Value
User 1 and User 4 - rate requirement	128 Kbps
User 2 and User 5 - rate requirement	256 Kbps
User 3 and User 6 - rate requirement	512 Kbps
$F_{i,th}$ for RA	0.3
$F_{i,th}$ for RR	0.15

The users are uniformly distributed in the cell area and their position is randomly chosen at the moment the current channel realization starts. Propagation losses, such as path loss (suburban profile) and shadowing are simulated. Fast fading is also simulated as a Rayleigh process.

There are many different choices to assign values to the select SNR cumulative probability thresholds. In this work, we intend to avoid that the user reports subcarrier channel gains that will result in "poor" SNR values. In our case, the term "poor" SNR values means that this SNR could not achieve the minimum SNR required to even transmit in the lower available scheme (2-QAM). Based on Figures 1, 2 and 3, the SNR cumulative probability thresholds were defined as $F_{i,th} = 0.15$ and $F_{i,th} = 0.3$, for the RR and RA algorithm, respectively. This difference is comprehensive and it is due

the distinct algorithm approaches, we can observe that RA algorithm schedules the user with the smallest achieved data rates and those ones could present bad channel conditions.

In Figure 4, we observe the performance of PPM for the RR algorithm. One can note the PPM does not change the performance of the RR algorithm, and both achieved data rates attain the rate requirements for each user. Sometimes, there are short differences between them (-0.42%, 4.11%, 8.83%, -1.70%, -5,21% and 7.23%).
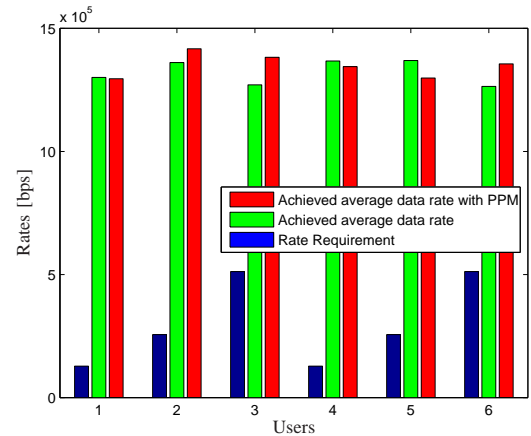

Fig. 4. Rate requirements and achieved data rates with and without pre-processing method, using RR algorithm with $F_{i,th} = 0.15$.

In Figure 5, we see the performance of PPM for the RA algorithm. Similar to RR algorithm case, one can observe that PPM does not change the performance and both achieved data rates (with and without PPM) attain the rate requirements for each user. Short differences observed between them (4.68%, 1.56%, 7.08%, -1.20%, 1.95% and 6.83%).
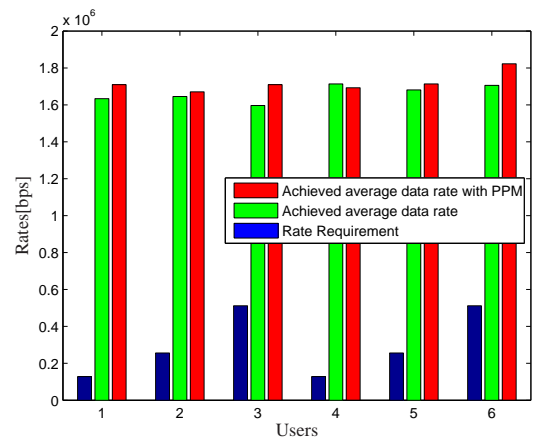

Fig. 5. Rate requirements and achieved average data rates with and without pre-processing method, using RA algorithm with $F_{i,th} = 0.30$.

Although the results with PPM were quite similar from the initial results without PPM, PPM has permitted mobile users to save about 9,33% to 18,67% (14 - 28 subcarriers over 100 total) of CSI reported to the base station in both RA and RR algorithms, i.e., in average, the mobile user did not reported 9,33% a 18,67% of the channel gains of his

subcarriers. These results may be seen in Figure 6 and 7. This is an important result since we show a waste of resources for reporting CSI. We have then used a limited feedback using the PPM, conserving the achieved average data rate.
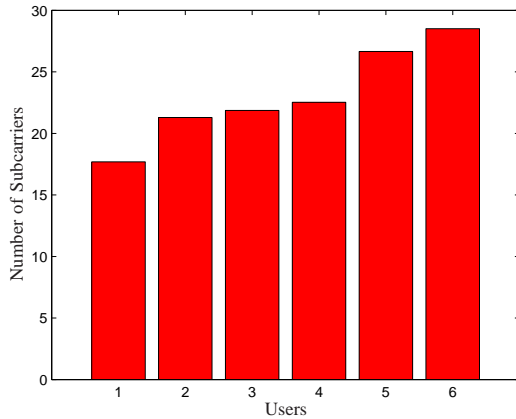

Fig. 6. Number of subcarriers not reported to the base station per user, using RR algorithm with a $F_{i,th} = 0.15$.
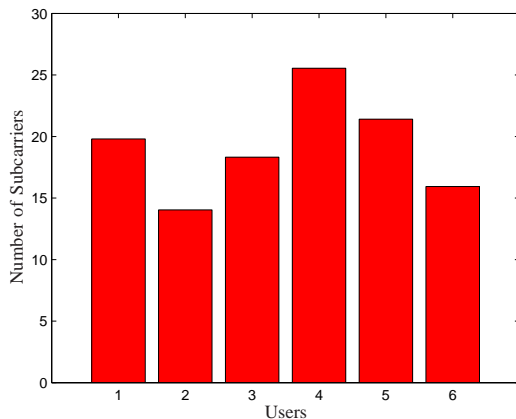

Fig. 7. Number of subcarriers not reported to the base station per user, using RA algorithm with a $F_{i,th} = 0.30$.

VI. CONCLUSIONS AND PERSPECTIVES

We have presented a new pre-processing method called PPM, which allows to decrease the amount of CSI reported from the mobile user to the base station, limiting, without loss, the required feedback from the mobile terminal. This goal is achieved looking at two new curves presented in this paper, each one maps the cumulative distribution function of SNR values from the scheduled users. These curves were obtained to the RR and RA algorithms.

The new technique PPM described enables the mobile user saves about 9,33% a 18,67% of required CSI reported to the base station preserving the characteristics of the original algorithm, i.e., the effects on QoS parameters (represented by average data rate) were imperceptible.

A direct extension to this work is the investigation of the PPM effects using adaptive thresholds and different scheduling algorithms.

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