UNIVERSIDADE FEDERAL DO CEARÁ
DEPARTAMENTO DE ENGENHARIA DE TELEINFORMÁTICA
CURSO DE MESTRADO EM ENGENHARIA DE TELEINFORMÁTICA

Redução do feedback requerido em sistemas de comunicações sem fio usando a abordagem Cross-layer

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FORTALEZA – CEARÁ
MAIO, 2008

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Dissertação submetida à Coordenação do Programa de Pós-graduação em Engenharia de Teleinformática da Universidade Federal do Ceará como parte dos requisitos para obtenção do grau de Mestre em Engenharia de Teleinformática.

Área de Concentração: Sinais e Sistemas.

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FORTALEZA – CEARÁ
MAIO 2008

Acknowledgements

This master of science thesis is a result of three important things: love, dedication and good infrastructure.

So, firstly, I would like to thank God and my family. God, for giving me the great opportunity to live, blessing me with health and lightening my way. My dad and mom, for their endless love. They were beside me everyday in all moments in this long journey, especially my mom whom taught me the first steps to be an engineer. Gisele, for being more than a sister, she was my life example, a kind friend and gave me all sort of help. My brother Eduardo, a very special guy who supported my undergraduate studies for a longtime.

Secondly, I want to thank my soul mate and husband, Rafael. His patience and love were unique. He was my partner at the engineering disciplines, helped me with the housework and made life easier.

I want to express my gratitude to my supervisor Dr. Charles Cavalcante. He was always available to discuss my work, believed in my potential and encouraged me to finish this document. Dr. Walter Freitas, who gave me important suggestions since the beginning ideas. Dr. Rodrigo Cavalcanti, who gave me some important insights and the opportunity to join the Wireless Telecommunications Research Group (GTEL).

I would like to thank my colleague and friend Darlan Moreira and all GTEL team. They were essential for the enhancement of my knowledge about wireless.

I would like to express my gratitude to Ericsson Brazil and Ericsson Sweden companies for their great support. Without their support, I could not have obtained these results. Their competent staff encouraged me to develop a good job and their financial and infrastructure supports were also very important.

I recognize that this research would not have been possible without the infrastruture of the Federal University of Ceará, of the Department of Teleinformatics of Federal University of Ceará and of FUNCAP (Fundação Cearense de Apoio à Pesquisa) financial assistance.

Resumo

Algumas soluções têm sido criadas, em ordem de maximizar a eficiência dos sistemas de comunicações sem fio, utilizando a adaptação de parâmetros do sistema de acordo com as variações do canal. A maioria destas soluções requerem o envio de informação precisa para o transmissor usando o canal de feedback. Entretanto, a largura de banda do canal de feedback é limitada e a redução de feedback é um assunto bastante explorado nos dias atuais. Neste trabalho, nós propomos construir uma curva empírica da função de distribuição cumulativa (CDF, do inglês, Cumulative Distribution Function) de valores da razão sinal-ruído (SNR, do inglês, Signal-to-Noise Ratio) dos usuários selecionados. Esta curva CDF é importante na escolha do limiar de SNR e reflete as características de aplicação e informações sobre políticas de escalonamento. Baseados nestas curvas, limiares são definidos com o objetivo de evitar o envio desnecessário de informação de canal. Duas modificações dos algoritmos foram sugeridas, respectivamente, para reduzir a quantidade necessária de informação de feedback e aprimorar a justiça entre usuários, sem degradação considerável no desempenho do sistema. A primeira modificação consiste de não enviar informação sobre o canal do usuário quando a SNR deste usuário for menor que o limiar, reduzindo assim a carga do canal de feedback. A segunda modificação é a ferramenta que leva em conta taxa atingida, em que somente os usuários com requerimentos de taxa de dados não preenchidos são considerados na alocação de recursos corrente, aumentando a justiça do sistema. Simulações computacionais confirmam o potencial das propostas e mostram o compromisso entre a redução de feedback e o desempenho do sistema.

Abstract

Some solutions have been created for wireless communication systems in order to maximize efficiency, by adapting system parameters according to channel variations. Most of them require the report of accurate channel information to the transmitter using a feedback channel. However, the bandwidth of the feedback channel is limited and feedback reduction is a hot research subject nowadays. In this work, we propose to build an empirical Cumulative Distribution Function (CDF) of Signal-to-Noise Ratio (SNR) values from chosen users. This CDF curve is important on SNR threshold choice and reflects characteristics of application and information about algorithm policies. Based on these curves, thresholds are defined in order to avoid reporting unnecessary Channel State Information (CSI). Two modifications of resource allocation algorithms were suggested to reduce the necessary feedback information and improve user fairness, respectively, without considerable system degradation. The first one consists of not reporting channel information when the SNR is lower than a threshold, therefore reducing the burden on the feedback channel. The second one is the rate awareness feature, where only users with fulfilled data rate requirements are considered in current resource allocation, increasing the system fairness. Computer simulations confirm the potential of the proposals and show the trade-off between feedback reduction and system performance.

List of Acronyms

3G	Third Generation
4-PSK	4 Phase-Shift Keying
16-QAM	16 Quadrature Amplitude Modulation
64-QAM	64 Quadrature Amplitude Modulation
AP	Access Point
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
BLAST	Bell Labs Layered Space-Time
CDF	Cumulative Distribution Function
CSI	Channel State Information
FDD	Frequency Division Duplex
FFT	Fast Fourier Transform
G2+1	MIMO scheme with one coded layer and one uncoded layer
GTEL	Wireless Telecommunications Research Group
LTE	Long Term Evolution
MAC	Medium Access Control
MCAS	Modulation, Coding and Antenna Scheme
MIMO	Multiple Input Multiple Output
NRT	Non-Real Time
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access

OSI	Open Systems Interconnection
PRB	Physical Resource Block
PF	Proportional Fair
PHY	Physical Layer
PSK	Phase Shift Keying
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
RA	Rate Adaptive
RLC	Radio Link Control
RM	Rate Maximization
RR	Round Robin
SISO	Single Input Single Output
SMS	Short Message Service
SNR	Signal-to-Noise Ratio
TDD	Time Division Duplex

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Chapter 1

Introduction

1.1 Motivation and objectives

Beyond Third Generation (3G) wireless networks, new applications will be offered to the users. Originally, cellular networks were created with the purpose of transmitting mainly voice. By the time, audio-conference and Short Message Service (SMS) were also provided. On the other hand, wired networks were created to transmit mainly data services like file transfers and to send e-mail, video or photo. These two distinct networks have evolved in such a way that they have come together and their services are integrated. Nowadays, cellular phones and computer networks have quite similar functionality and they provide almost the same services.

This integration could bring out serious problems to the networks, even though, these networks have a framework in common. The most used framework is the Open Systems Interconnection (OSI) model which is composed of seven independent layers: physical, link, network, transport, session, presentation and application [1]. These layers have been created to have some functions in such a way that this function is executed in only one layer. The layer functioning is independent of those of other layers.

The OSI reference model was applied to the first cellular systems whose main planned function was the transmission of voice. In the Physical Layer (PHY), a “worst-case” approach was used in order to combat the wireless channel impairments with satisfactory performance. On the other hand, with the introduction of new services with different Quality of Service (QoS) requirements, this approach is no longer suitable, especially with the fast increasing of requirements for current and future generations of cellular systems.

Design constraints are also very important. In order to adapt to the large demand of user services, installing new network equipments is not a good idea, because it could increase the existent interference among networks, have some environment impacts and it is often very expensive.

Therefore, to support the high data rates and variable QoS requirements of future networks, a high flexibility of the involved layers is necessary and optimizing each layer individually is not enough anymore. A cross-layer design [2] is then desirable to actively exploit the dependence between protocol layers and obtain performance gains.

A cross-layer design is not exclusive to wireless systems and several works have investigated the benefits of cross-layer policies [3–8]. The channel dynamics is the main reason why the OSI model does not fit wireless systems as well as it does to wired ones.

A very common problem to be solved, in wireless systems, is to predict the radio channel and combat wireless link impairments [9]. The PHY continuously generates detailed information about the current radio channel conditions, known as Channel State Information (CSI). Therefore, CSI can be used to solve this explained problem. Also, the Orthogonal Frequency Division Multiplexing (OFDM) transmission technique and the use of multiple antennas at the transmitter and at the receiver[1] increase greatly the degrees of freedom of the system providing a lot of flexibility. However, this flexibility also means more feedback information to be reported and makes the constraint of the feedback channel bandwidth more important. In fact, ideally the user would have to report to the base station its CSI for each subcarrier in the OFDM symbol for each pair of transmitting and receiving antennas, which is clearly impractical. Even when considering a grid of subcarriers and OFDM symbols as one resource block with only one associated CSI, the quantity of necessary feedback information to be reported may be still impractical since the feedback channel is shared by all users in the system.

The multidimensional link adaptation consists of changing the Multiple Input Multiple Output (MIMO) scheme and Modulation according to a target Bit Error Rate (BER). At the same time, the resource allocation of the available Physical Resource Blocks (PRBs) is done for the users in the system according to one of the available schedulers: Round Robin (RR), Rate Adaptive (RA), Rate Maximization (RM) or Proportional Fair (PF).

In this dissertation, we propose methods for reducing the amount of feedback information to be reported by the users in a wireless environment. Based on the knowledge about the Cumulative Distribution Function (CDF) of the Signal-to-Noise Ratio (SNR) of chosen users, we propose an empirical CDF curve to help with the selection of SNR threshold to be reported. The rationale is to avoid the reporting of information for the not scheduled users, since this curve is used as a cross-layer issue in order to avoid the unnecessary feedback.

1.2 Publications

- **Pre-Processing Effects for Limited CSI Feedback in Scheduling Algorithms using Cross-Layer Issues**, Cibelly Azevedo de Araújo, Charles Casimiro Cavalcante, Walter da Cruz Freitas Júnior. *XXV Brazilian Telecommunications Symposium*, 2007, Recife-PE.

- **On the Modeling and Evaluation of the Physical Layer of HSPA Uplink**. Elvis Miguel Galeas Stancanelli, Emanuel Bezerra Rodrigues, Jean Marcelo Maciel, Cibelly Azevedo de Araújo, Francisco Rodrigo Porto Cavalcanti. *XXV Brazilian Telecommunications Symposium*, 2007, Recife-PE.

1.3 Thesis Structure

The remainder of this work is organized as follows:

- Chapter 2 - some explanation about the cross-layer approach, required feedback and resource allocation. Some related works in the literature are presented and, finally, the resource allocation algorithms are also described.

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[1] These two techniques are key aspects to obtain the high data rates and QoS requirements of the future wireless systems.

- Chapter 3 - The problem of subcarrier allocation is described for a scenario with a Single Input Single Output (SISO) channel. An empirical CDF curve is proposed and some results are shown.

- Chapter 4 - A MIMO channel is considered in the resource block allocation. The SNR threshold and *Rate Aware* features are evaluated to reduce required feedback and some results are presented.

- Chapter 5 - states the main goals obtained with some concluding remarks and perspectives.

Chapter 2

Cross-Layer, Resource Allocation and Information Feedback in Wireless Systems

2.1 Overview

Some background material is presented in this chapter. Important aspects have been used as a basis for the proposals of the following chapters. In this chapter, we intend to introduce some useful and elucidating concepts in this work, as follows:

- Firstly, a brief explanation about cross-layer approaches is presented.
- The trade-off of interaction among layers and the required feedback information is established.
- The importance of resource allocation for a good performance on wireless systems is presented.

2.2 What does Cross-Layer mean?

Some frameworks were created in order to establish communication among different networks and to reuse network components. The most popular used framework is the Open Systems Interconnection (OSI) model. OSI model is composed of seven independent layers: physical, link, network, transport, session, presentation and application [1]. These layers were planned to execute their inherent functions without the help of any other layer. Therefore, each layer is responsible for a well-defined subset of system operation functions and it adds or removes (depending on the information direction) its header to the received data and passes it to the adjacent layer. With this approach, each layer has evolved with considerable research efforts to improve the efficiency of its protocol independently of the other layers [5, 6].

Improvements on each layer were quite simple to be done due the fact the other layers were considered as black boxes. Therefore, each layer could optimize its parameters in order to achieve better performance and adapt them to the new functionalities. The great deal is this optimization process, finding the optimum of one specific layer parameter could waste a considerable amount of network resources, or processing, and this optimum would not necessarily bring expressive performance gains for the overall system. It seems clear that system performance improvements could arise with some communication among different layers, if the system allows certain smart interaction among them. This foresight has led to a new paradigm: cross-layer optimization [6].

Even though a cross-layer design is not exclusive of wireless, this term is most common in these systems and several works have investigated the benefits of cross-layer policies [3–8]. This aspect is particularly important to wireless systems where channel impairments are always present and, theoretically, a new optimization should be executed when any physical characteristic changes. Thus, the channel dynamics is the main reason why the OSI model does not fit wireless systems as well as it does to wired ones. In fact, the layer directly affected by the channel dynamics, the Physical Layer (PHY), is so important that it is possible to divide cross-layer design in two cases: any layer interacting with PHY layer and upper layers interaction [6].

Cross-layer optimization can be performed in a number of ways and the choice of the involved layers and the metrics are key aspects on such task. This is usually also related to an increase in the feedback information which is necessary to perform the Cross-layer optimization. In our case, where the integration is between the PHY and Medium Access Control (MAC) layers the feedback information is used by the resource allocation algorithm and link adaptation[1]. In systems where similar channels for the downlink and uplink[2] could not be assumed, this feedback information must be reported to the transmitter using a “feedback channel”. This imposes a constraint in the allowed feedback information since this channel usually has a fairly limited bandwidth.

Among these possibilities it is possible to highlight two common cases in the literature: cross-layer interactions between PHY and MAC layers [5–8, 10], and cross-layer interactions between PHY and Application layers [11–13]. In this work we are dealing with the problems related to the former.

2.3 Cross-Layer Approaches

As stated in Section 2.2, the cross-layer interaction can be done in several ways and the choice of the best one depends on the application. However, some issues must be considered on the cross-layer design for any application [6]:

- The trade-off between the feedback associated with the cross-layer interaction and the efficiency improvement must be analysed;
- What is the additional feedback needed to extract relevant parameters from one layer that could be useful for other layers?
- An appropriate feedback channel must be identified and reserved to transfer information between layer entities.

It is possible to classify the cross-layer approaches with several criteria. Regarding the possible structures, we can divide them into two main categories:

- Each layer is modified according to the cross-layer interaction with other layers, i.e., some internal parameter of each layer must be modified taking into account some information

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[1] The link adaptation in our case corresponds to the choice of the modulation and the Multiple Input Multiple Output (MIMO) scheme to be used.

[2] This corresponds to most actual systems which use Frequency Division Duplex (FDD) instead of Time Division Duplex (TDD).

about the state of other layers. For instance, the structure of the MAC layer can be modified when it is known that a deep fading is present in the channel;

- An external entity manages the cross-layer interactions and defines the corresponding interfaces and primitives with each layer. This method hides most of the complexity of the cross-layer interaction in a single entity.

2.3.1 Trade-off between cross-layer efficiency and feedback

The idea that the interaction among different layers can result in system performance improvements is intuitive. However, when targeting cross-layer interaction, a number of feedback bits turn up. For instance, the use of PHY layer information in upper layers requires certain overhead to transport PHY layer information and also training sequences may be necessary for the estimation of Channel State Information (CSI). Besides, when cross-layer interaction is done between remote nodes, it is necessary to use specific-purpose feedback channels and carefully analyze the trade-offs of performance improvements versus required feedback. Hence, the following issues should be addressed [6]:

- Number of entities and layers involved in the cross-layer information exchanges;
- Definition of useful CSI or proper information values for cross-layer adaptation;
- The increase in feedback load associated with the extraction and transmission of the desired parameter;
- The degree of robustness to channel errors. This is more crucial in scenarios of high mobile speed;
- Timing and delay constraints, regarding the processing capabilities of the involved entities;
- The resulting benefits in terms of system performance.

Taking into account this trade-off, it is possible to distinguish three categories of cross-layer design described below [6].

1. The first category does not involve transmission of any additional information between layers. The cross-layer interaction consists of an active effort by one protocol layer to deduce the state of the other protocol layers by effectively looking inside packet headers or by making intelligent deductions from the traffic pattern. An example of this category could be the prioritization of transport-layer acknowledgment packets by data-link layer, which has been shown in [14] to improve the performance of wireless schemes by reducing the number of time-outs at the transport-layer. However, this approach has some constraints with the use of secure protocols, which imply that headers from other layers are encrypted.

2. The second category involves the transmission of additional information from one layer to another without changing the actual protocol interface, that is, only extra information and processing are added into the primitive packets in order to react in each layer, according to the variations of the other layers, without modifying none of the primitives of all the protocols in the protocol stack.

3. The third category aims at modifying the protocols and their interfaces so that the most useful information is transmitted down between the layers. This category is destined towards more long-term goals and includes the cross-layer classical concept as it has been generally understood.

2.3.2 Definition of control information for cross-layering

In order to minimize the feedback mentioned in Section 2.3.1 associated with cross-layer approach, the relevant parameters to be exchanged among layers will depend on the functionalities being considered for cross-layer interaction and on specific air interfaces and system concepts. Based on the kind of information exchanged among layers, we can classify the cross-layer interaction in four categories as follows [6]:

1. Based on CSI: the information exchanged among layers includes estimates at channel impulse response, location information, mobile speed, signal strength, interference level, matrix conditioning, etc. Since the PHY layer associated with the CSI is the most variant layer, this is the case with the most feedback.

2. Based on QoS-related parameters: the information exchanged among layers includes delay, throughput, bit error rate (BER), packet error rate (PER) measurements, etc.

3. Based on Available Resources: the information exchanged among layers includes the available resources in the corresponding node, such as multi-user reception capabilities, battery depletion level, number and type of antennas, among others.

4. Based on Traffic Pattern: the information exchanged among layers includes data traffic information, knowledge of the data rate, data burstiness, data fragmentation, packet size, information about queue sizes, etc.

2.3.3 Classification of cross-layer interactions

There is a wide range of possible cross-layer interactions, which have an impact on types of information that must be exchanged, therefore, on the channel used to actually transmit this information. Regarding the entities performing cross-layer approach, we can divide the cross-layer interactions into the following categories [6]:

- Cross-layer inside a single node: there is communication among different layers of the protocol stack of a single node, but no information is exchanged among layers of different nodes. Therefore, there is only an extra processing associated with the use of the cross-layer approach.

- Cross-layer between remote nodes: there is communication among different layers of the protocol stack of remote nodes. In this case, one node can adapt its layers based on measurements or estimations done in the remote node. For instance, the MAC layer of a base station can give priority to the user with better CSI sent to the base station through the feedback channel.

Regarding the number of layers performing cross-layer, the simplest cross-layer approach involves only two layers that communicate with each other in order to optimize transmission and it is where most of the research is focused. In principle, the cross-layer interaction can concern any of the OSI layers and all the possibilities present potential benefits. However, since the PHY is the most time-variant entity in a wireless communication system, the cross-layer interactions can be classified, regarding the type of layers performing cross-layering, into two main categories [6]:

- Any layer interacting with PHY: The layer interacting with the PHY can adapt to the CSI. Any layer (MAC, Radio Link Control (RLC), routing, application, etc.) in order to improve system efficiency.

- Upper layer interaction: the variability of the layers involved should probably appear as a consequence of an indirect influence with other system parameters or situations such as congestion, application hardware failure, etc.

2.3.4 Scenarios

Even the simplest case of cross-layer interaction with only two layers provides a wide range of possibilities and it is necessary to find a well-established scenario which can represent the effects from the different layers. We will focus our attention on the integration of the PHY with MAC including both remote nodes and a single node.

We will use the performance gain provided by the joint optimization as a success criterion in the scenario of a multiuser Single Input Single Output (SISO) (see Chapter 3) and MIMO (see Chapter 4) downlink resource allocation in an Orthogonal Frequency Division Multiplexing (OFDM) system. That is, with the cross-layer integration the system is able to use the multiuser diversity in the resource allocation problem to assure Quality of Service (QoS) requirements of the overall system. After the resource allocation algorithm, other conventional ways to improve the system performance such as link adaptation can be used in a per user basis.

2.4 State of the art

The term cross-layer optimization actually covers a large research field to be explored. That is, the cross-layer communication can be done with different number of layers and the optimization can be done according to different resources (data rate, QoS, energy consumption, etc.). An example of cross-layer interaction among physical layer and upper layers of two remote nodes is shown in Figure 2.1, where the different control flows are represented by arrows. An entity called “Agent Manager” estimates, measures and selects the appropriate values to be sent to the upper layers of the transmitting node. These layers will adapt accordingly to the actual channel condition, performing the cross-layer interaction. This Agent is responsible for setting up and formatting control information, so that the cross-layer overhead is minimized [6].

This example outlines only one possibility of cross-layer interaction. It is also possible to have a cross-layer interaction between two layers of the same node of the communication system or even between layers not shown in Figure 2.1.

It is worth noting that in each specific communication system, the suitability of the application of a certain cross-layer interaction should be carefully studied in order to assess that real system enhancements could be achieved [6]. One of the reasons is the trade-off between cross-layer efficiency and the overhead associated with it.

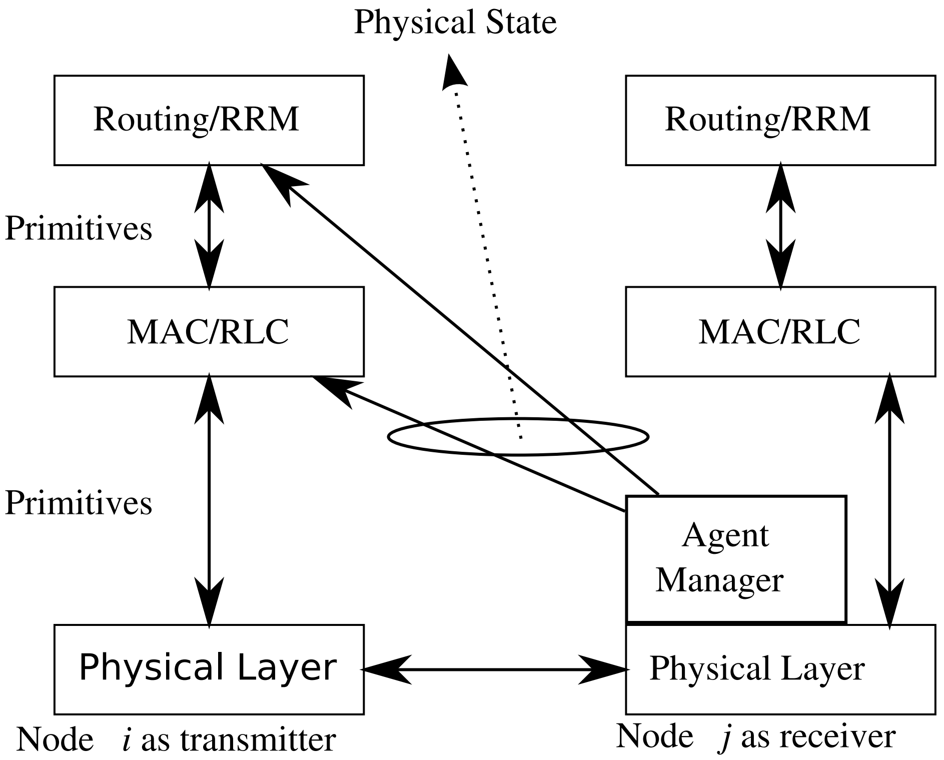

Figure 2.1: Example of cross-layer interaction through an Agent Manager.

In recent years research efforts focused on cross-layer design have been progressively increased with different focuses. In [7] a theoretical framework is proposed to build a bridge between the physical layer and MAC layer and to balance efficiency and fairness using utility functions. The algorithm development for this framework is done in [8]. In this case the cross-layer interaction tries to maximize the throughput of the system by allocating the subcarriers among the users in an OFDMA system with a constraint associated with the fairness, followed by power allocation in each subcarrier (bit-loading).

On the other side, in [15] the cross-layer interaction tries to optimize the energy consumption in order to save battery of portable devices. It is based on the lazy scheduling principle proposed in [16] and whose idea is that transmitting at a lower rate requires less transmitting power and, therefore, it adapts the user rate to his actual requirements.

In [17] the trade-off between multi-user diversity and spatial diversity is analyzed with a centralized scheduler that makes extensive use of physical layer measures. The idea is to compare the different antenna selection options and the different space-time-code strategies in order to evaluate their impact in the throughput and average system capacity. A possible bandwidth constraint of the feedback channel is also considered.

In [18], the system capacity with reduced feedback was studied in a SISO single-cell system. It was considered the capacity model defined by Shannon, given by:

$$C(j,n) = \log_2(1+\gamma_j(n)), j = 1,\dots,J \text{ and } n = 1,\dots,N. \tag{2.1}$$

where j is the current user, J is the number of active users on the system, n is the current slot, N is the total number of simulated slots, $\gamma_j(n)$ is the Signal-to-Noise Ratio (SNR) during the slot n for the user j. It is suggested a γ_{th} in function of the outage probability and J such that if the user has a SNR below γ_{th} it will not report its CSI. A Rayleigh fading channel is considered and all J users have the same average SNR γ_j. The feedback channel is shared with all users and then collision is possible. The impact of the choice of γ_{th} in the system capacity is then analytically analysed for the Proportional Fair (PF) and Rate Maximization (RM) algorithms.

In [19], a SISO single-cell system was modeled with a frequency-selective channel with time-frequency correlation, where the OFDM technique is used to obtain a flat-channel per subcarrier. At the start of the simulation a user position is randomly chosen, such that the users are uniformly distributed in the cell area. Rate Adaptive (RA) and Round Robin (RR) algorithms are used for the resource allocation and it is suggested an empirical Cumulative Distribution Function (CDF) curve and a SNR threshold based on this curve.

In [20], a SISO single-cell system with Rayleigh channel is considered. This system is co-operative allowing mobile terminals to communicate with each other and the feedback channel is modeled as a shared contention based channel. First, the Access Point (AP) sends a pilot signal for all users to allow them to estimate their channel quality and selects one of them randomly. If the selected user (j) can transmit with the highest allowed modulation, it sends the AP an acknowledgement through the feedback channel and it is selected to transmit. Otherwise, the user j sends its supported modulation to the other users and, if one of them supports a better modulation, it sends an acknowledgement to the user j that will then inform the AP about the found user. If a collision occurs and the user j is not able to find a unique user with better modulation than his, the AP selects a new user j' and re-starts the loop until one user is selected for transmission or all the users have been requested.

2.5 Resource Allocation

To analyse the link adaptation and the resource allocation performance, four classical approaches have been chosen to be implemented on MAC Layer: RR, RA, RM and PF. Their features and particularities are explained in the sequel. These approaches have quite general use, but in this specific purpose, subcarriers are considered to be the allocated resources.

Let **X** indicate the resource allocation matrix whose elements $x_j(k)$ are defined as

$$x_j(k) = \begin{cases} 1, & \text{if subcarrier } k \text{ is assigned to user } j \\ 0, & \text{otherwise.} \end{cases} \tag{2.2}$$

Hence, r_j is the data rate of user j, defined as:

$$r_j(\mathbf{X}) = \sum_{k=1}^{K} c_j(k) \cdot x_j(k). \tag{2.3}$$

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2.5.1 Round Robin

The RR is implemented as a cyclic queue of users. Each user is sequentially and periodically scheduled to transmit in one unit of resource, 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 its great advantage, but users with different QoS requirements could be placed in disadvantage.

As it can be noted, the algorithm is not sensitive to current user CSI, since the CSI is not taken into account into the resource allocation process.

2.5.2 Rate Adaptive

The RA concept is to maximize the lower throughput bound ϵ of each user, i.e., the lowest mobile user throughput is maximized. The cost function is defined as [21]:

$$\begin{aligned} &\max_{\varrho,\mathbf{X}} \ \epsilon, \\ &\text{subject to} \quad \sum_k F(\rho_j(k), P_{err}) \cdot x_j(k) \geq \epsilon \quad \forall j. \end{aligned} \tag{2.4}$$

where $\rho_j(k)$ is the SNR value of the j-user at the k-th subcarrier, ϱ is the JxK matrix representing the set of all SNR values from all J users at all K subcarriers, P_{err} is the error probability, $\mathbf{X}$ is the resource allocation matrix and $x_j(k)$ is the $\mathbf{X}$ equivalent element of the j-th user at the k-th subcarrier.

We have implemented the Rhee's suboptimal algorithm [22]. In each algorithm iteration, it searches for the user with the lowest current achieved data rate and assigns one unit of resource for this user. This algorithm aims to guarantee a minimum data rate for the worst-case user. Therefore, it gives a sort of fairness if the data rate requirements of the users are equal, but it is unfair when these requirements are not equal.

2.5.3 Rate Maximization

The RM approach intends to maximize the system throughput by allocating each unit of resource to the user whose channel allows the highest spectral efficiency. That is, this approach allocates the unit of resource to the user that achieves the highest data rate for that specific unit of resource based on the link adaptation output (Section 4.3). Therefore, the cost function is defined as [21]:

$$\begin{aligned} &\max_{\varrho,\mathbf{X}} \sum_j \sum_k F(\rho_j(k), \mathbf{P}_{err}) \cdot \mathbf{x}_{j,n}. \\ &\text{subject to} \quad \sum_k p_k \leq p_T, \quad \forall k \end{aligned} \tag{2.5}$$

where $\rho_j(k)$ is the SNR value of the j-user at the k-th subcarrier, ϱ is the JxK matrix representing the set of all SNR values from all J users at all K subcarriers, P_{err} is the error probability, p_k is the transmit power at the k-th subcarrier, p_T is the total transmit power, $\mathbf{X}$ is the resource allocation matrix and $x_j(k)$ is the $\mathbf{X}$ equivalent element of the j-th user at the k-th subcarrier.

As it can be noted, the user CSI is directly employed in the resource allocation process, since the resource is allocated to the user whose channel allows the maximum spectral efficiency without considering any kind of fairness.

2.5.4 Proportional Fair

The PF approach allocates the resources based on the user CSI and achieved data rates. It can be considered as a mixture of the RM and RA algorithms. The cost function is defined as [23]:

$$\begin{aligned} &\max_{\varrho,\mathbf{X}} \sum_{j} \sum_{k} F(\rho_j(k), \mathbf{P}_{err}) \cdot \mathbf{x}_{j,n}. \\ &\text{subject to} \frac{r_j(k)}{\Upsilon_j} \geq \frac{r_l(k)}{\Upsilon_l} \quad \forall j,l \in J. \end{aligned} \tag{2.6}$$

where $\rho_j(k)$ is the SNR value of the j-user at the k-th subcarrier, ϱ is the JxK matrix representing the set of all SNR values from all J users at all K subcarriers, P_{err} is the error probability, $r_j(k)$ and $r_l(k)$ are the supported data rates of the j-user and l-user at the k-th subcarrier, respectively. Υ_j and Υ_k are the achieved throughputs of the j-th and l-th user, $\mathbf{X}$ is the resource allocation matrix and $x_j(k)$ is the $\mathbf{X}$ equivalent element of the j-th user at the k-th subcarrier.

Therefore, PF is sensitive to the users CSI as in the RM approach and has some fairness characteristics as in the RA algorithm.

2.6 Summary

This chapter reviews some important aspects to be considered in this thesis. They will serve as a basis for the understanding and development of the proposals. The main subjects discussed here were:

- The definition and possibilities of cross-layer approach.
- The relation between cross-layer efficiency and necessary feedback.
- Some works with the objective to inform some state-of-the-art issues.
- And finally, we have presented some resource allocation algorithms.

In the next chapters, the aspects presented here will be used and we will propose some new strategies to reduce the required feedback.

Chapter 3

Resource Allocation in a SISO Channel Scenario

3.1 Overview

This chapter focuses on:

- Proposition of an empirical Cumulative Distribution Function (CDF) curve, in order to help to establish a Signal-to-Noise Ratio (SNR) threshold.
- Single-cell evaluations for the use of the obtained SNR threshold and determination of the amount of non-reported subcarriers using Single Input Single Output (SISO) channels.

3.2 System Architecture

In this work, a single-cell system is assumed in which one base station can transmit to J mobile users. As an Orthogonal Frequency Division Multiple Access (OFDMA) system, the cell spectrum W is split into a set of K subcarriers. The number of subcarriers (K) is chosen sufficiently large to permit that each subcarrier can be seen as an individual flat fading channel. Thus, subcarriers are modeled as K flat Rayleigh fading channels with correlation in time and frequency domains.

A number of n Orthogonal Frequency Division Multiplexing (OFDM) symbols were used in performance analysis. In order to restrain the problem, for each OFDM symbol, it is assumed that each subcarrier is assigned only to one user. Each user is modeled with full data buffer using Non-Real Time (NRT) services with different data rate requirements. It is assumed that each j-th mobile user has knowledge of his own complex channel gain $H_j(k)$ on the k-th subcarrier and can transmit, without errors and instantaneously, its Channel State Information (CSI) to the base station. The SNR $\rho_j(k)$ of the j-user at the k-th subcarrier is defined as [7]:

$$\rho_j(k) = \frac{|H_j(k)|^2 \cdot p}{\eta_j(k)}, \tag{3.1}$$

where p is the subcarrier transmitting power, which is considered to be equal in all K subcarriers and $\eta_j(k)$ represents the Additive White Gaussian Noise (AWGN) power density function of user j at the k-th subcarrier. The SNR $\rho_j(k)$ 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 $c_j(k)$ of the j-th user at the k-th subcarrier is given by [8]

$$c_j(k) = w \cdot \log_2 \left[1 + \beta\rho_j(k)\right], \tag{3.2}$$

where w is the subcarrier bandwidth and β is the SNR gap for the system Bit Error Rate (BER) requirements defined as [8]

$$\beta = -\frac{1.5}{\ln(5 \cdot \text{BER})}. \tag{3.3}$$

.

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. Figure 3.1 shows a simplified and discrete model of the link adaptation scheme which is composed of different levels representing transitions between data rates. Each transition SNR value is called M-QAM SNR threshold, $\rho_{M-\text{QAM}_{th}}$, and its corresponding available data rates, $c_{M-\text{QAM}_{th}}$. A quantization process is done in order to match the possible transmitting data rates to the available data rates and it is made a comparison between the user SNR per subcarrier $\rho_j(k)$, and the M-QAM SNR threshold $\rho_{M-\text{QAM}_{th}}$, as shown in the Algorithm 3.1.

Algorithm 3.1 Pseudo-Code of the comparison between SNR values

```
if $\rho_j(k) < \rho_{2-\text{QAM}_{th}}$ then
    $r_j(k) = 0$ (no transmission)
end if
if $\rho_j(k) > \rho_{64-\text{QAM}_{th}}$ then
    $r_j(k) = c_{64-\text{QAM}_{th}}$
end if
if $\rho_{M-\text{QAM}_{th}} \leq \rho_j(k) \leq \rho_{(M+1)-\text{QAM}_{th}}$ then
    $r_j(k) = c_{M-\text{QAM}_{th}}$
end if
```

3.3 Empirical CDF Curve

In our approach, an empirical curve is created in order to make the SNR threshold choice. For obtaining this curve, some characteristics were extracted from the resource allocation algorithms in order to foresee the user possibilities of being chosen to transmit in the next OFDM symbol.

The performance of different users with different rate requirements was evaluated. Several channel realizations per user have been simulated and, at the moment that each user was chosen to transmit in a specific subcarrier, the equivalent SNR was stored. In the next step, the CDF $F_{\rho_j(stored)}(\cdot)$ of SNR values from all stored subcarriers owned by the j-th user was calculated by the following:

$$\begin{aligned} \rho_j(stored) &\longrightarrow F_{\rho_j(stored)}(\rho_j(stored)) \\ F_{\rho_j(stored)}(\rho_j(stored)) &= \Pr(\varrho \leq \rho_j(stored)), \quad \forall \rho_j(stored), \end{aligned}$$

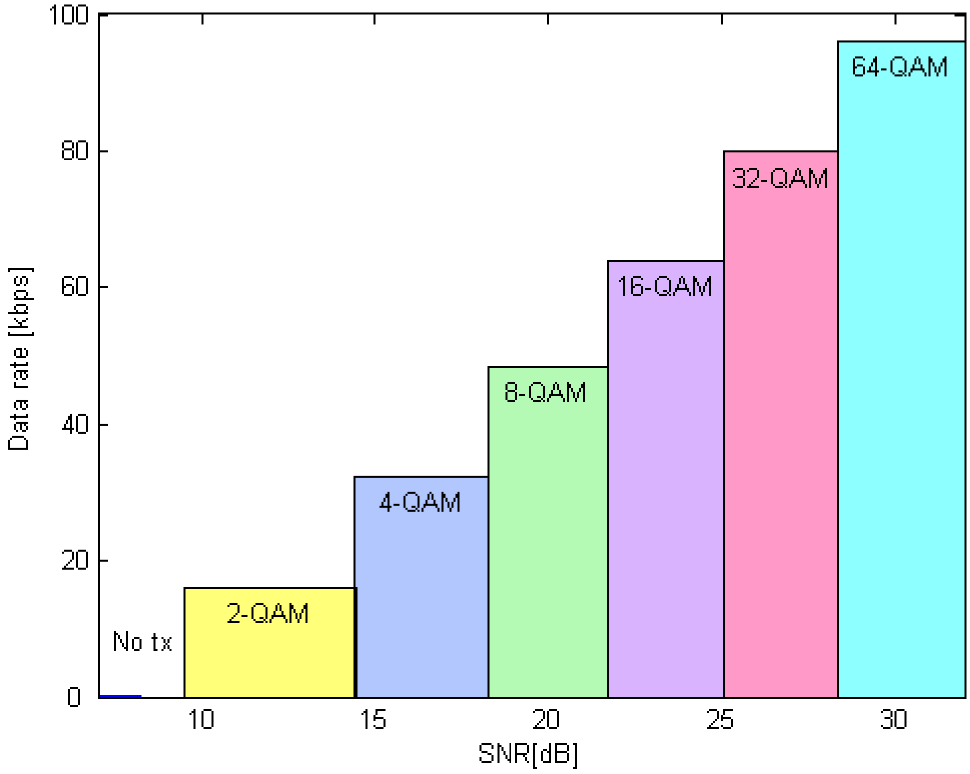

Figure 3.1: Simplification of link adaptation scheme.

where $\rho_j(stored)$ are the SNR values of the stored subcarriers of the j-th user and ϱ is a random variable.

Six users were simulated with Round Robin (RR) algorithm and the equivalent CDF curves for this algorithm are shown in Figure 3.2. In the same way, six users were simulated with Rate Adaptive (RA) algorithm and the equivalent CDF curves for this algorithm are shown in Figure 3.3.

Depending on the used algorithm, the CDF curve inherently reveals the Quality of Service (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 resource allocation algorithm policies. Physical layer could then use this additional information on making its proper decisions, as a cross-layer approach.

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

$$\begin{aligned} \rho_j(k) &\longrightarrow F_{\rho_j(stored)}(\rho_j(k)) \\ F_{j,th} = F_{\rho_j(stored)}(\rho_{j,th}(k)) &= Pr(\varrho \leq \rho_{j,th}(k)) \\ F_{\rho_j(stored)}(\rho_j(k)) &> F_{j,th}, \quad \forall \rho_j(k), \end{aligned}$$

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

With the defined SNR threshold, mobile users may report only subcarrier channel gains whose corresponding SNR values are greater than $\rho_{j,th}(k)$. For the non-reported subcarrier channel gains,

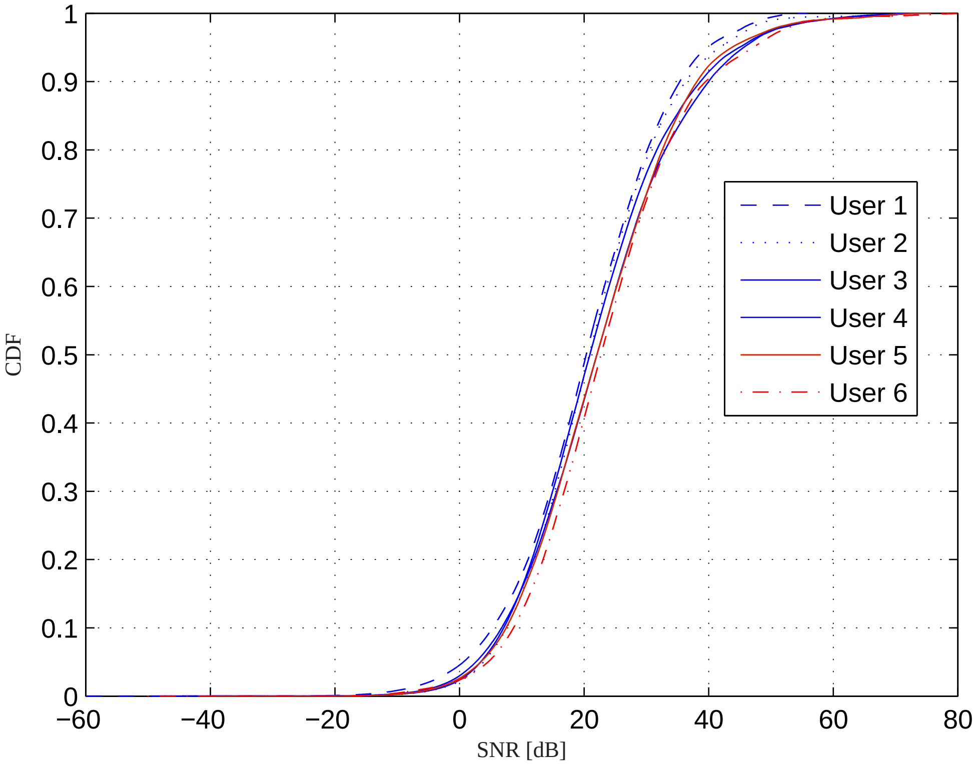

Figure 3.2: Typical CDF for Round Robin algorithm with 6 users.

mobile users turn off the signalling transmission of these subcarriers, but in case of this work, just for implementation reasons, pre-established 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 $\rho_{j,th}(k)$. For instance, only the users whose SNR values are greater than this threshold $\rho_{j,th}(k)$ for a specific subcarrier k are considered for the allocation of this subcarrier k.

In the RR algorithm case, firstly, the user is chosen, 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 $\rho_{j,th}(k)$, are included in the resource allocation process. This fact is due to the RR algorithm concept where all subcarriers must be signalled to the user, independent of his subcarrier channel gains.

We must keep in mind that CDF curve is a powerful feature to avoid reporting unnecessary information, but a high $F_{j,th}$ has different impacts depending on the used resource allocation algorithm. We can deduce, from the RA algorithm description in Chapter 2, that as the $F_{j,th}$ increases, the average system data rate also increases and the priority of users experiencing bad channel conditions decreases. Thus, the CDF curve could bring about system data rates improvements. A similar analysis could be done with the RR algorithm description in Chapter 2, where it can be deduced that the system data rate stays the same or gets worse.

Therefore, the $F_{j,th}$ definition is an important trade-off to be evaluate in the simulations. In

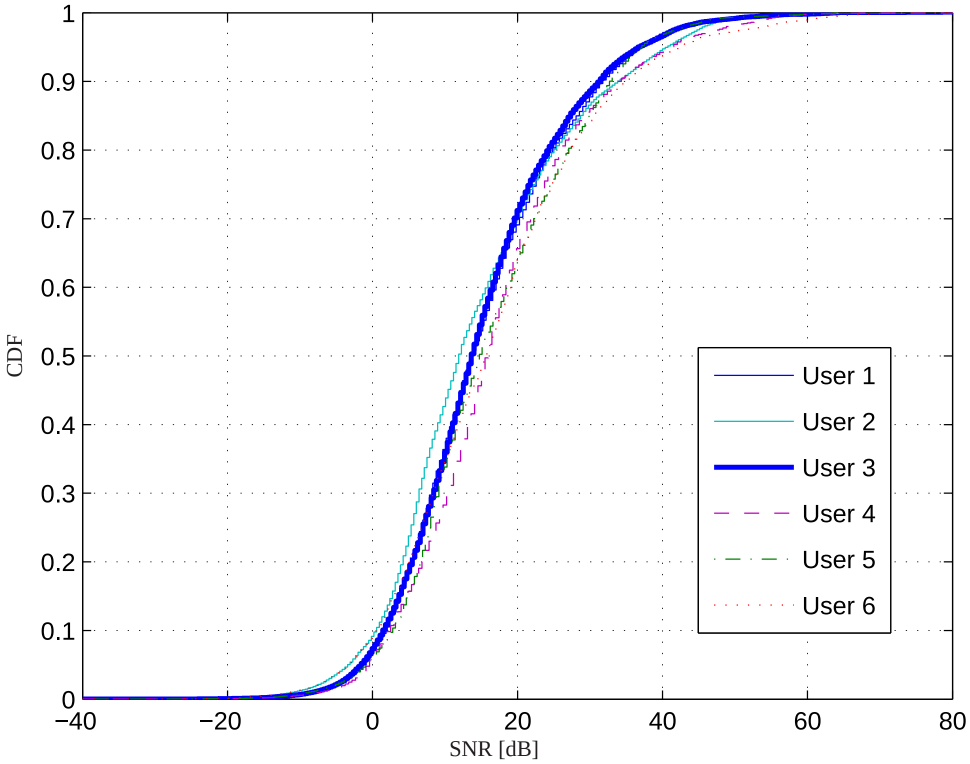

Figure 3.3: Typical CDF for Rate Adaptive algorithm with 6 users.

addition, Figures 3.2 and 3.3 show that a fixed $F_{j,th}$ corresponds to a distinct SNR region for the resource allocation algorithms.

3.4 Simulation 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 3.1.

Table 3.1: 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 is assumed a single-cell system model with one base-station and six users with different data rate requirements, as presented in Table 3.2. We have used 200 channel realizations and each channel realization has 2400 OFDM symbols. For implementation reasons, used algorithms allocate a sub-frame with 8 OFDM symbols, i.e., the transmission has the same configuration on the whole sub-frame.

Table 3.2: Data rate parameters for performance evaluation.

Parameter	**Value**
User 1 and User 4 - data rate requirement	128 Kbps
User 2 and User 5 - data rate requirement	256 Kbps
User 3 and User 6 - data rate requirement	512 Kbps
$F_{i,th}$ for RA	0.30
$F_{i,th}$ 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 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 transmit, even in the lower available scheme (2-QAM). Based on Figures 3.1, 3.2 and 3.3, the SNR cumulative probability thresholds were defined as $F_{j,th} = 0.15$ and $F_{j,th} = 0.30$, for the RR and RA algorithm, respectively. This difference is intuitive and it is due to the distinct algorithm approaches. It can be observed that RA algorithm chooses the user with the smallest achieved data rates and those could present bad channel conditions.

In Figure 3.4, we observe the performance of RR algorithm. One can note the SNR threshold does not change the performance of the RR algorithm, and both achieved data rates attain the rate requirements for each user. Sometimes, there are small differences between them (-0.42%, 4.11%, 8.83%, -1.70%, -5,21% and 7.23%).

In Figure 3.5, the performance of the RA algorithm is shown. Similar to RR algorithm case, one can observe that SNR threshold use does not change the performance and both achieved data rates (with and without the use of SNR Threshold) attain the rate requirements for each user. Some small differences were observed between them (4.68%, 1.56%, 7.08%, -1.20%, 1.95% and 6.83%).

Although the results with the use of SNR threshold were quite similar to the initial results without its use, it has allowed 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 report 9,33% to 18,67% of the channel gains of his subcarriers. These results may be seen in Figure 3.6 and 3.7. This is an important result since we show a waste of resources for reporting CSI. We have then used a limited feedback using the SNR threshold, conserving the achieved average data rate.

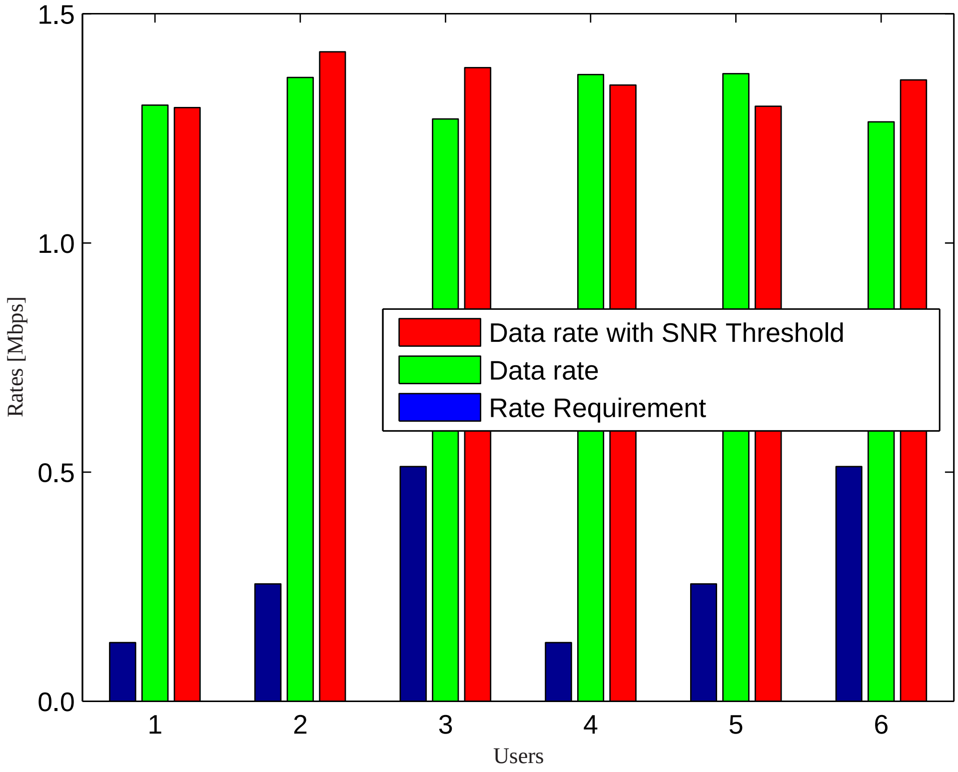

Figure 3.4: Rate requirements and achieved data rates with and without the use of SNR threshold, using RR algorithm with $F_{j,th}$= 0.15.

3.5 Summary

We have presented an empirical CDF curve which allows choosing a SNR threshold, in order 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 by looking at two curves presented in this paper. Each one maps the cumulative distribution function of SNR values from two different resource allocation algorithms. These curves were obtained from the RR and RA algorithms.

The use of SNR threshold enables the mobile user to save about 9,33% to 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.

In this chapter, it is discussed the use of a SNR threshold feature in a SISO wireless channel. In the next Chapter 4, it will be discussed the use of this feature and a new one called Rate Aware in a Multiple Input Multiple Output (MIMO) channel.

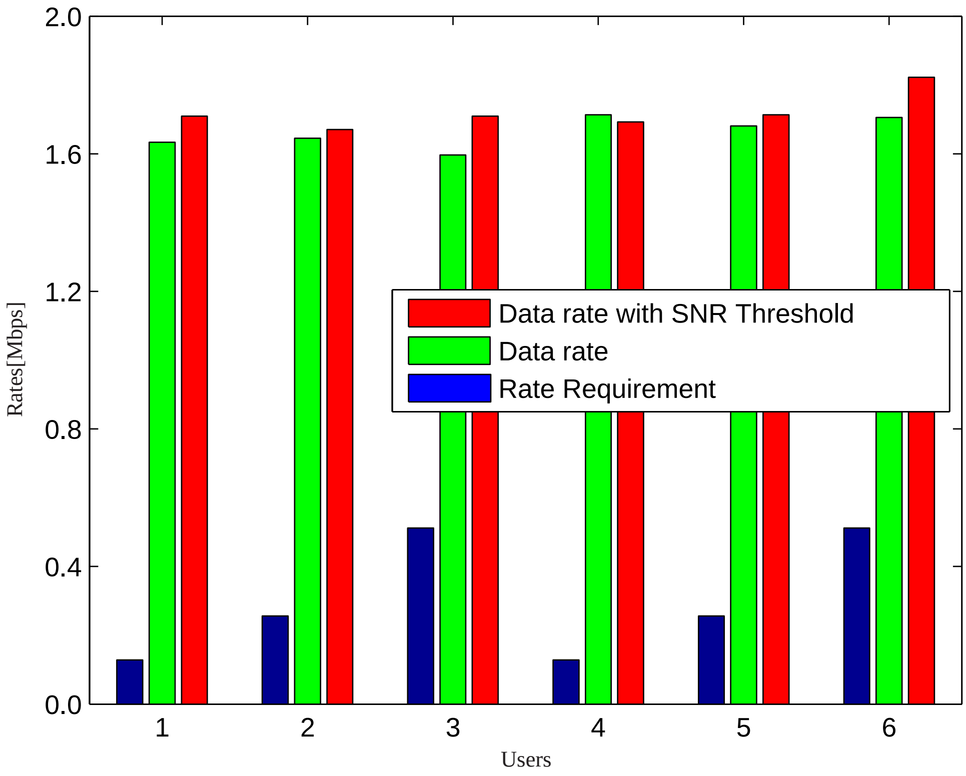

Figure 3.5: Rate requirements and achieved average data rates with and without the use of SNR threshold, using RA algorithm with $F_{j,th}$= 0.30.

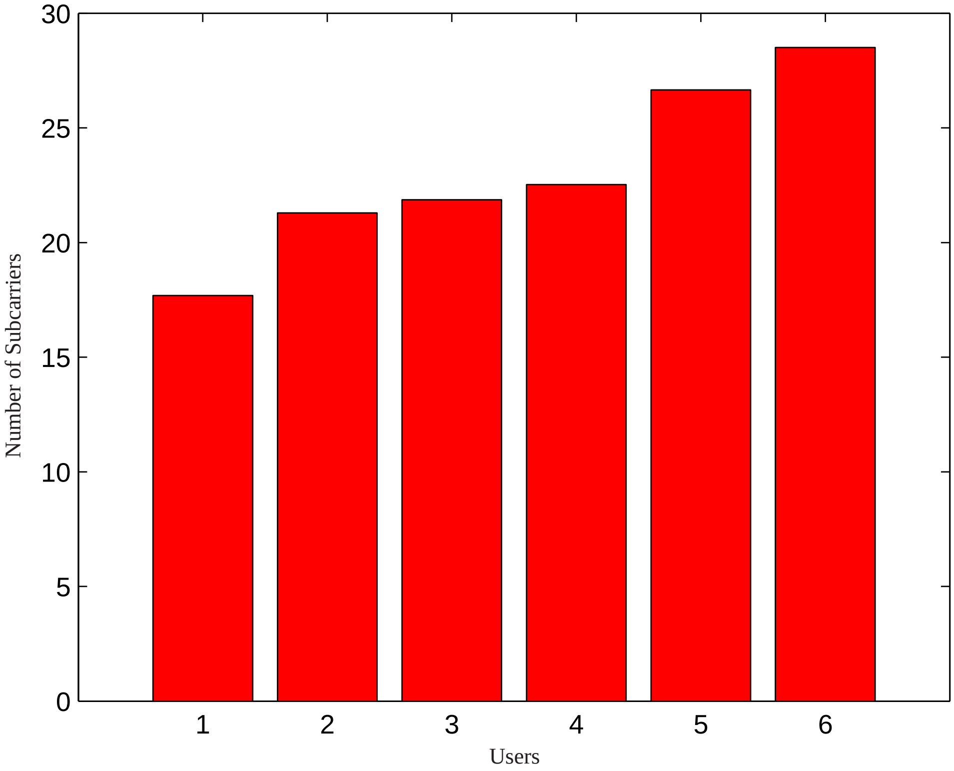

Figure 3.6: Number of subcarriers non-reported to the base station per user, using RR algorithm with a $F_{j,th}$ = 0.15.

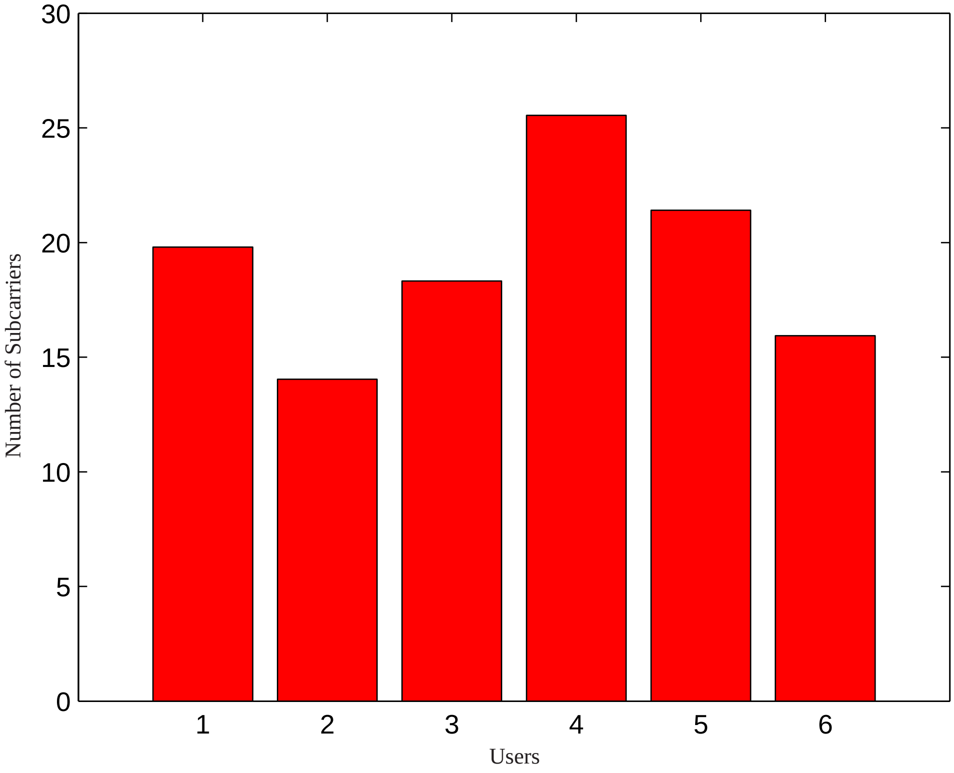

Figure 3.7: Number of subcarriers non-reported to the base station per user, using RA algorithm with a $F_{j,th}$ = 0.30.

Chapter 4

Resource allocation in a MIMO Channel Scenario

4.1 Overview

In Chapter 3, an empirical feedback scheme for the Frequency Division Duplex (FDD) downlink Orthogonal Frequency Division Multiple Access (OFDMA) was proposed. The resource allocation is dealing with subcarriers with a reduced number of users and uses a Single Input Single Output (SISO) transmission scheme. What would be different if we had used a Multiple Input Multiple Output (MIMO) channel? This is the main aspect to be studied in this chapter.

This chapter presents:

- Two approaches to modify the resource allocation algorithms in order to reduce the required feedback.
- Single-cell evaluations for the proposal methods using MIMO channels.

4.2 Problem Description and System Model

In this chapter, a FDD downlink OFDMA of MIMO cellular wireless network is considered. This network is composed of one base-station with 3 transmitting antennas and 18 users, each one with 3 receiving antennas. It is considered that the u-th user has a data rate requirement of 512 Kbps and a fixed average Signal-to-Noise Ratio (SNR) $\overline{\gamma}_u$. In order to improve the gains of multi-user diversity, at the simulation beginning, an average $\overline{\gamma}_s$SNR is defined, half of the users have their $\overline{\gamma}_u$ equal to $\overline{\gamma}_s$ and the other half of the users have their $\overline{\gamma}_u$ equal to $\overline{\gamma}_s$ plus a boost of 5 dB. It does not characterize a real world scenario, but in this case, it is not so important to have a high fidelity of user mobility neither of large-scale fading. On the other hand, it is sufficient to provide a framework for the evaluation of the link adaptation and resource allocation algorithms.

The present study makes use of a simulation tool built on C++ and a ten-tapped frequency-selective Rayleigh fading channel was created, using the available features on IT++ library [24]. The used bandwidth has 20 MHz and each subcarrier has a bandwidth of 15 KHz. Inspired in the Long Term Evolution (LTE) system, each Orthogonal Frequency Division Multiplexing (OFDM) symbol has 1200 subcarriers to be allocated among the users [25][1].

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[1] The size of the Fast Fourier Transform (FFT) used is 2048, but only 1200 subcarriers are actually used.

In practice, the subcarriers are allocated in blocks and not individually. That is, the minimum resource block that can be allocated to a user, is a grid in the time-frequency domain, which in this work, is composed of twelve subcarriers and seven subsequent OFDM symbols [2] as shown in Figure 4.1. As a consequence of this resource block allocation, one hundred resource blocks are available to be allocated.

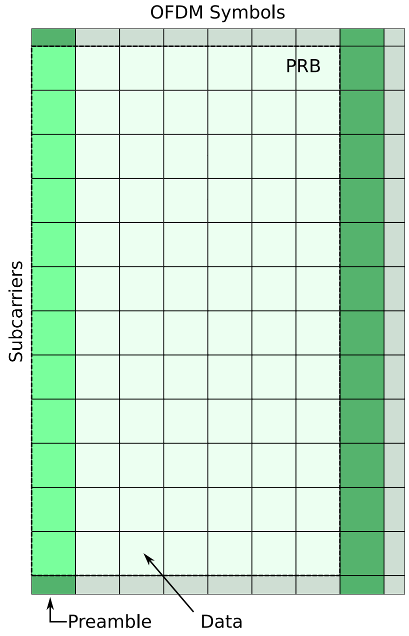

Figure 4.1: Resource Block composed of 12 subcarriers and 7 OFDM symbols.

Figure 4.2 shows the simulation results considering only one user in the system transmitting everytime in all subcarriers with the same Modulation, Coding and Antenna Scheme (MCAS). For each simulation, it was fixed one of those available MCAS: MIMO scheme with one coded layer and one uncoded layer (G2+1) with 4-Phase Shift Keying (PSK), G2+1 with 16-Quadrature Amplitude Modulation (QAM), G2+1 with 64-QAM, Bell Labs Layered Space-Time (BLAST) with 4-PSK, BLAST with 16-QAM or BLAST with 64-QAM. With this simulation, the achieved Bit Error Rate (BER) was obtained in function of the average SNR.

For a BER target of 10^{-3}, Figure 4.2 shows that even for the most robust MCAS (G2+1 with 4-PSK) the BER target will not be achieved for an SNR below 13dB. Therefore, this value was chosen as the SNR threshold.

Each user measures the SNR for each resource block. If this SNR is above the SNR threshold, the user reports the SNR for this specific block to the base-station through the feedback channel. Otherwise, the SNR for this specific block is not reported. Thus, this resource block will be called a non-reported resource block for that user. In Figure 4.3, the number of non-reported resource blocks is illustrated for the Proportional Fair (PF) Algorithm. Note that the horizontal axis shows the average SNR value. The actual SNR value of one user is the average value plus the fast fading and, if present, the SNR boost.

Since the decision to report the user Channel State Information (CSI) is only based on its SNR value, this curve is independent of the chosen resource allocation algorithm. As it can be observed in Figure 4.3, a considerable number of feedback information can be saved since there is a large

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[2] The first OFDM symbol is a preamble and it is not used to transmit data.

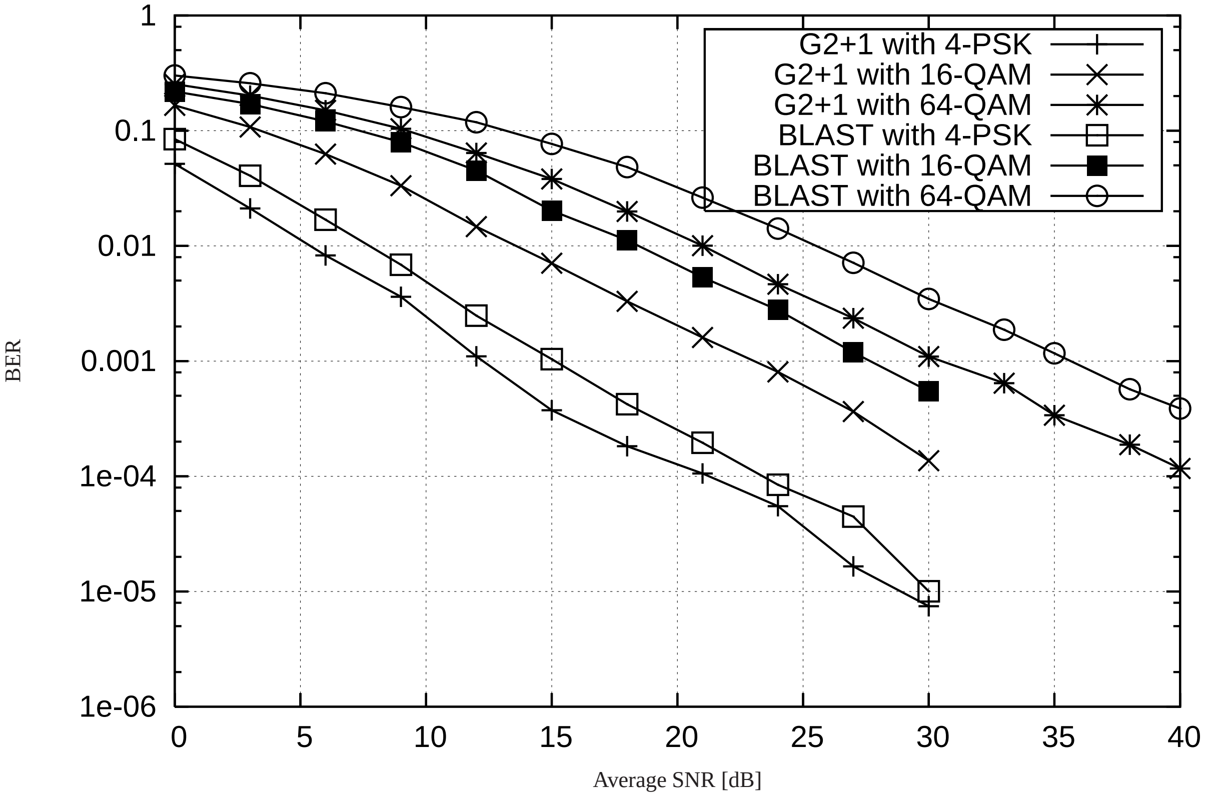

Figure 4.2: Performance of the various MCAS.

number of non-reported resource blocks. Otherwise, using these resource blocks would transmit some additional bits, but these additional bits could raise the BER. Thus, not transmitting the user CSI[3] for that resource block preserves the BER below the BER target, while saving precious bandwidth of the shared feedback channel.

For instance, we can see from Figure 4.3 that below an average SNR value of 12dB the users CSI for at least 77,78% of the resource blocks (around 1400) were not necessary to be reported[4]. That is, for lower SNR values it is better not to transmit the user CSI and not to consider this user at all in the resource allocation process for that block. If no user could claim this resource block, it is just assumed that it should use the most robust MCAS.

4.3 Link Adaptation

Regarding the link adaptation, three different modulations (4 Phase-Shift Keying (4-PSK), 16 Quadrature Amplitude Modulation (16-QAM) and 64 Quadrature Amplitude Modulation (64-QAM)) and two different MIMO schemes (G2+1 [26] and BLAST [27]) are available. To perform the link adaptation, it is necessary to have some metric to compare the different combinations

---

[3] When the base station does not receive the CSI from the user for one resource block, then the user will not claim that resource block and it will not be considered in the resource allocation process unless no user has transmitted its CSI for that block.

[4] Considering that each user has 100 resource blocks, the total number for 18 users is 1800 resource blocks.

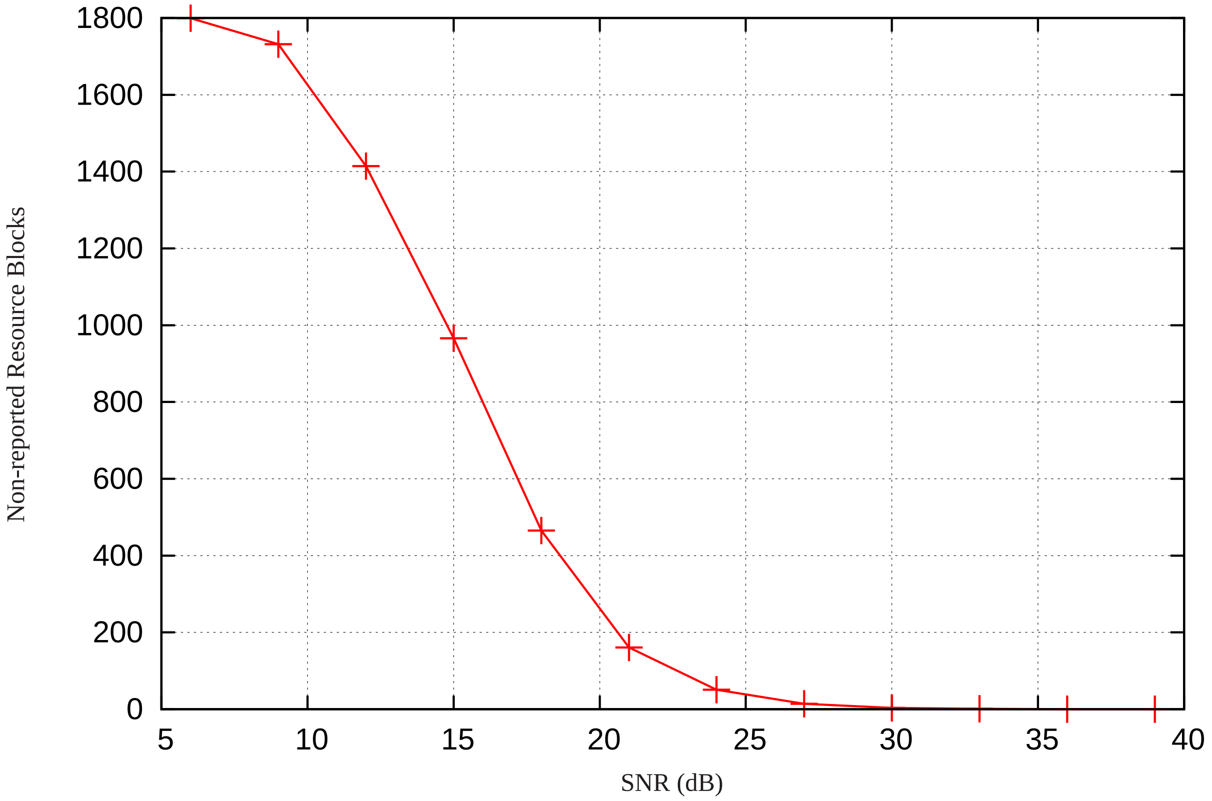

Figure 4.3: Number of non-reported resource blocks to the base-station as a function of the estimated SNR, with 18 users using SNR Threshold and Rate Aware features.

of transmitting parameters which are, in this case, the modulation and the MIMO scheme. In particular, computer simulations were performed for each combination to determine the SNR of the crossing points from one combination to another. That is, the SNR value that achieves a target BER of 10^{-3} for each combination of modulation and MIMO scheme. After that, the parameters that achieve the target BER and yield best spectral efficiency are chosen. However, two aspects must be considered: how do we map the MIMO channel to a single SNR value and how to map the SNR of all subcarriers in the resource block into a single value for the resource block?

In [28] the performance of space-time receivers is analyzed and an equation for the resulting SNR is presented for the zero-forcing receiver that can be used to map the MIMO channel in a value of equivalent SNR for each independent stream for the BLAST scheme as described by the following equation:

$$\eta_k = \frac{\rho}{M_T} \frac{1}{[(\mathbf{H}^H\mathbf{H})^{-1}]_{k,k}}, \tag{4.1}$$

where η_k is the resultant SNR for the k-th stream, $\rho = \frac{E_s}{N_0}$ (Symbol energy E_s / noise power N_0), $\mathbf{H}$ is the MIMO channel, M_T is the number of transmitting antennas and $[\cdot]_{k,k}$ is the k-th element in the diagonal of a matrix.

In the case of the G2+1 MIMO scheme, the equation can still be used to determine the SNR of the uncoded stream. Since the uncoded stream dominates the BER, this value can be used as an estimate of the SNR for the G2+1 MIMO scheme. While, at first sight, it appears that BLAST and

G2+1 schemes will have the same performance with this approach, one should note that the actual BER curves are different for the same mapped SNR value, since the G2+1 scheme has lower BER than the BLAST scheme because of the diversity protection of the coded layer. However, a better approach for mapping the MIMO channel to a resultant SNR value for the G2+1 scheme is still desirable.

For the problem of mapping the resultant SNR value of all subcarriers in a resource block to a single value for the whole one to be employed in the resource allocation process, the used approach is to consider the SNR of a single subcarrier, for instance, the subcarrier in the centre of the resource block, as the resultant SNR for the whole one.

4.3.1 Proposals for resource allocation

In order to maximize the number of satisfied users, i.e., the number of users that achieve the required data rate with a BER below a specified upper bound, two modifications to the algorithms presented in Chapter 3 were performed: rate awareness and SNR thresholds.

Rate Awareness

In this policy, each user stores its data rate requirement and achieved data rate. This achieved data rate is updated when some modification in the resource allocation process occurs [5]. If this user has already achieved its data rate requirement, it cannot claim a resource block until this condition becomes false.

The rate awareness aims to avoid a waste in resource utilization by excluding satisfied users from the scheduling queue, benefiting the other users. If there are no unsatisfied users, then the scheduler chooses a user, randomly.

SNR Threshold

In order to reduce the amount of CSI reported to the transmitter for each resource block, an SNR threshold is defined such that the users with SNR below this threshold do not report their CSI. This idea was already implemented in [19] and [18].

When the user CSI is not reported for one resource block, the user cannot claim this resource block and he will not be considered in the resource allocation process for that resource block, unless no other user has transmitted its CSI for that resource block, which is then allocated to a random user.

The threshold was chosen as the SNR value for which the most robust MCAS achieves the highest BER below the BER upper bound. This approach is justified by the fact that when the SNR is lower than this threshold, the obtained BER is higher than the acceptable upper bound. Therefore, it is better to save feedback bandwidth by not transmitting the user CSI.

4.4 Numerical Results

In Figure 4.4 the satisfaction for all algorithms is shown for the case where *Rate Aware* and *SNR Threshold* features are disabled.

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[5] When a new OFDM allocation starts or some resource block is allocated for this user.

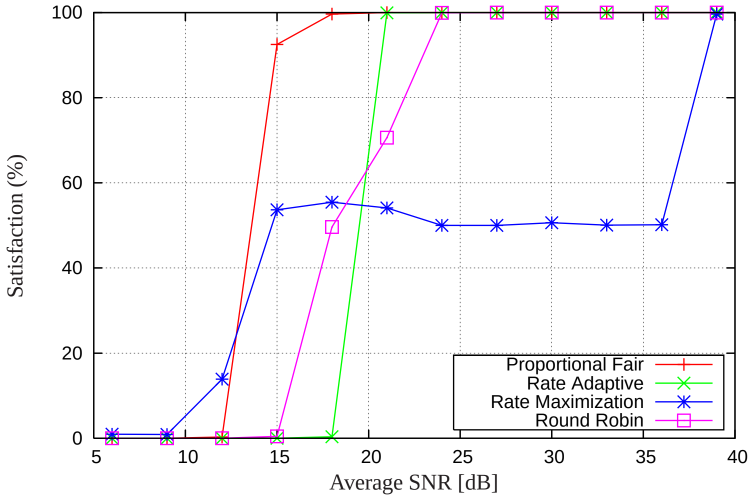

Figure 4.4: Satisfaction with *Rate Aware* and *SNR Threshold* features disabled.

The fact that half of the users have an SNR increase has a direct impact in the algorithm performances. It can be observed, for instance, that the Rate Maximization (RM) algorithm achieves approximately 50% satisfaction for the SNR value of 15dB. Below this value, practically all users are in the same *link adaptation range*, i.e. they can achieve the same spectral efficiency with the target BER. For the SNR value of 15dB, half of the users will be allowed to use a higher MCAS and will receive the available resources. As the SNR values grow, the users can switch to a higher MCAS, but the resource blocks are always allocated to the half of the users with an SNR boost, resulting in the system satisfaction of 50%. The system satisfaction reaches 100%, only when the SNR is higher enough so that all users end up in the highest MCAS and, therefore, all of them have the same spectral efficiency.

On the other side, the system satisfaction has an importance for the other schedulers and even for lower SNR values, some fairness is ensured. However, for the scenario of 18 users with a data requirement of 512Kbps, the system throughput at low SNR is not enough to serve all the users while keeping some fairness and none of the users are satisfied. As the SNR value grows, each user can switch to higher MCAS, such that the users can be satisfied while keeping some degree of fairness.

In Figure 4.5 the satisfaction for all algorithms is shown for the case where *Rate Aware* and *SNR Threshold* features are enabled.

As it can be noted, all algorithms achieve the system satisfaction of 50% for an SNR equal to 9 dB. This is directly related to the *SNR Threshold*, since half of the users is above the threshold and the other half is below. Therefore, the system resources are shared only among these users who can actually achieve the target BER. Also, the *Rate Aware* feature grants the RM scheduler some fairness and it also achieves the satisfaction of 50% and even 100% earlier.

A curious behavior is seen in the Rate Adaptive (RA) algorithm where the system satisfaction is not monotonically increasing with the SNR. This is caused by the use of the SNR Thresholds. Below the SNR of 9dB, all users are below the threshold, which was chosen as 13dB, and the resource blocks are allocated in a random way. Therefore, the system throughput is not enough to satisfy the users, resulting in a system satisfaction of 0%. For an SNR value between 9dB and 13dB, half of the users with the SNR boost of 5dB are above the SNR threshold and the resource

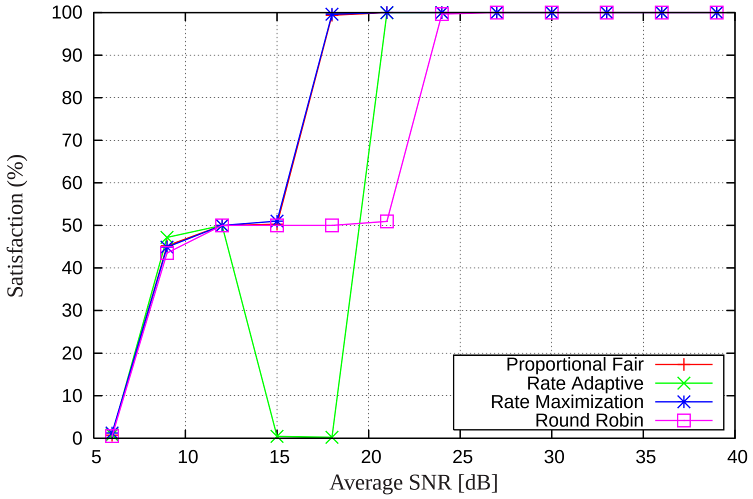

Figure 4.5: Satisfaction with *Rate Aware* and *SNR Threshold* features enabled.

blocks are allocated among these users resulting in a system satisfaction of approximately 50%. When the SNR is between 13dB and 18dB, all the users have an SNR above the threshold but the obtained system throughput is not enough to satisfy the users and the system satisfaction drops to zero. As in the case when the threshold is not considered, the system satisfaction is equal to 100% for an SNR above 21dB.

In Figures 4.6 and 4.7 the system throughput is shown for both cases, with *SNR Threshold* and *Rate Aware* features enabled and disabled.

The throughput for the Round Robin (RR) and RA algorithm did not change with the features on. On the other hand, the RA and PF algorithm had a throughput penalty due to the fact that these algorithms have chosen users with lower spectral efficiency to increase the system satisfaction.

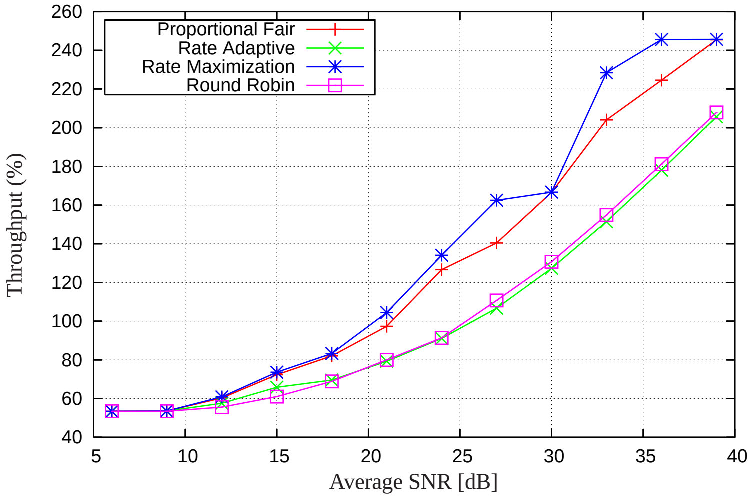

Figure 4.6: System throughput with *Rate Aware SNR Threshold* features disabled.

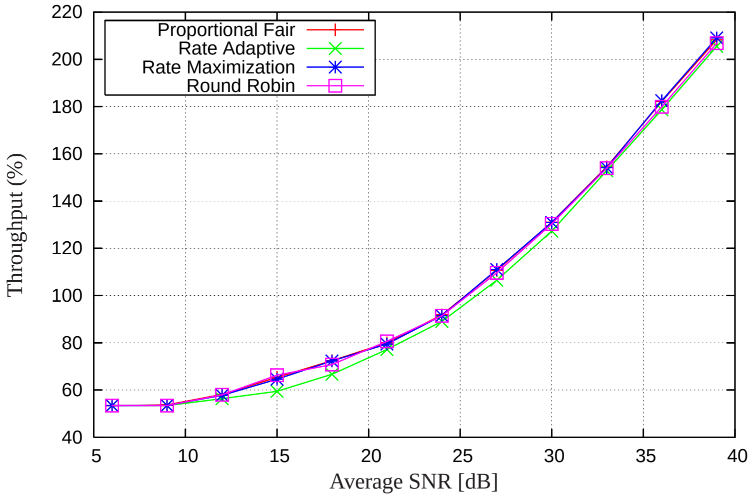

Figure 4.7: System throughput with *Rate Aware SNR Threshold* features enabled.

4.5 Summary

In MIMO-OFDMA systems, the flexibility from both techniques greatly increases the system degrees of freedom. The use of an SNR threshold to determine if the user should report its CSI can reduce the requested amount of feedback bits, specially for low values of SNR. Also, not considering these users in the resource allocation process[6], increases the system satisfaction.

On the other hand, the *Rate Aware* consideration is useful to increase the system satisfaction even though there is some throughput degradation caused by avoiding already satisfied users in the resource allocation process, releasing resources that can be allocated to other users, even when these users can achieve higher data rates.

Both strategies, SNR threshold and *Rate Aware*, are similar in a way that they avoid wasting system resources where it does not bring benefits. Despite the application in wireless systems, the *Rate Aware* feature can be extended to wireline systems with similar expected results.

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[6] Unless that all other users are satisfied.

Chapter 5

Conclusions and Perspectives

Firstly, we have presented an overview about cross-layer, resource allocation and information feedback. These issues are necessary to establish the basis to the proposed solutions. Some related works were discussed in order to justify the importance of this work.

Secondly, we have proposed an empirical Cumulative Distribution Function (CDF) curve of Signal-to-Noise Ratio (SNR) values from users that were selected to transmit. This CDF curve was very useful at the SNR threshold choice which is directly related with the amount of required feedback. Results presented in Chapter 3 confirm that, for a Single Input Single Output (SISO) channel, we have some important reduction of required feedback and small changes on the resource algorithm performances.

In Chapter 4, the SNR threshold choice was based on the minimum possible SNR to achieve the Bit Error Rate (BER) target of 10^{-3} for the most robust system Modulation, Coding and Antenna Scheme (MCAS). In order to improve the user fairness, we have proposed the *Rate Aware* feature.

For the evaluation purpose, a Multiple Input Multiple Output (MIMO) channel is used and the flexibility from both techniques greatly increases the system degrees of freedom. The use of an SNR threshold is a way to identify when it is worth transmitting channel information, allowing, therefore, the reduction of the large amount of feedback information that would be required in such systems. Also, this approach can be applied to different resource allocation algorithms without considerable system degradation.

On the other hand, the *Rate Aware* feature avoids already satisfied users being considered on the resource allocation process, releasing resources that can be allocated to other users. This approach is useful to give some fairness to the system, allowing the access of users without priority to be chosen to transmit. In fact, this feature avoids to transmitting the users with high priority and that have already achieved their data rate requirements, causing some throughput degradation.

Both strategies, SNR threshold and *Rate Aware*, are similar in a way that they avoid wasting system resources where if this does not bring benefits. Despite the application in wireless systems, the proposed methods can be extended to wired ones with expected similar results.

Concluding, we have two different approaches for the feedback reduction: the first one presented in Chapter 3 where the SNR threshold is chosen in order to avoid that a user sending its subcarrier Channel State Information (CSI) when it has small probabilities to be chosen to transmit. The second approach refers to Chapter 3 where it avoids the CSI report from one user that cannot transmit at the most robust scheme available on the system. Therefore the *Rate Aware feature* brings some user fairness as a user, with achieved data rate greater than its data rate requirement, is not allowed to transmit its CSI.

Some perspectives of this work are to establish a comparison among different choices of SNR presented in the literature and to evaluate the feedback channel with distortion and errors.

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