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Radio Resource Management for Pervasive Mobile Communication Networks

(Gestione della Risorsa Radio per Reti di Comunicazioni Mobili Pervasive)

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To Mum and Dad, who I owe everything.
To Dany, who shows me the truth.
And to whom is there, though not being here.

Science may set limits to knowledge,
but should not set limits to imagination.
Bertrand Russell

Table of Contents

Preface

Recently the demand of applications differentiated in terms of error rate, maximum delivery delay, et cetera, at possibly high speed data rates, has dramatically increased. To face these challenges, multi-carrier based air interfaces have been chosen for broadband wireless standards like Wireless interoperability for Microwave Access (WiMAX) and Long Term Evolution (LTE). In such context, a key role is played by scheduling and radio resource allocation, whose aim is allowing suitable sharing of radio resources among services.

The aim of this Thesis is to design and investigate radio resource allocation and scheduling strategies over multi-carrier wireless systems. The analysis considers different kinds of multi-carrier systems, like Orthogonal Frequency Division Multiple Access (OFDMA) and Multi Carrier-Code Division Multiple Access (MC-CDMA), various network architectures, like single-cell, multi-cell, hierarchical opportunistic networks, and different approaches, like cross-layer, centralized and distributed.

The main original contributions of this Thesis are the following: an extensive numerical evaluation of the advantages introduced by cross-layer resource allocation for multi-carrier cellular systems, with respect to traditional layered approaches, has been performed. Then, the cross-layer approach analyzed has been applied to an original opportunistic emergency-deployed network based on the opportunistic network paradigm. Finally, the problem of distributed scheduling and resource allocation over multi-cell multi-carrier systems has been faced, through the introduction of a novel technique, possibly extendible to infrastructure-less networks, which aims at making interference predictable.

Introduction

The most profound technologies are those that disappear. They weave themselves into the fabric of everyday life until they are indistinguishable from it, Mark Weiser said in his 1991 seminal paper [1] describing his vision of ubiquitous computing, now called *pervasive computing*, whose essence was the creation of environments saturated with computing and communication capability integrated with human users.

The objective of this Chapter is to make an *excursus* of the main concepts investigated in this Thesis, whose aim is to study radio resource allocation strategies in multi-carrier based systems, like OFDMA and MC-CDMA. The importance of such systems is that they allow the introduction in the resource allocation problem of a new dimension, *i.e.*, the multi-carrier one, which brings new potentialities thanks to the possible exploitation of frequency selectivity, turning what was considered in traditional systems as a disadvantage, into an advantage. The analysis of resource allocation strategies will be performed over different kinds of multi-carrier networks, like single-cell, multi-cell, or emergency-deployed networks, with different kinds of multi-carrier systems, like OFDMA and MC-CDMA, and with different approaches depending on the specific network under investigation, like cross-layer, centralized or distributed. All these aspects fit the main research topic of pervasive computing, as extensively illustrated in the following.

Pervasive computing is an evolutionary step from ideas originating in mid-1970s, whose intermediate stages were *distributed systems* and *mobile computing* [2]. From mid-1970s to 1990s a conceptual framework and algorithmic base for distributed systems was created based on a concept involving two or more computers connected by a network, with the following characteristics:

- remote communication [3];
- fault tolerance [4];
- high availability [5];
- remote information access [6];
- security [7].

The problems in building a distributed system arose with the appearance of full-function laptop computers and wireless Local Area Networks (LAN) in the early 1990s. At that point, the field of mobile computing was thus born. The following four key constraints due to mobility, forced the development of specialized techniques:

- unpredictable variations in network quality;
- lowered trust and robustness of mobile elements;
- limitations on local resources imposed by weight and size constraints;
- concern for battery power consumption.

Since motion is an integral part of everyday life, mobility support is a must and pervasive computing has to subsume mobile computing, while trying to go further by including four additional features:

- effective use of smart spaces;
- invisibility;
- scalability;
- uneven conditioning of environments masking.

So, a key idea under pervasive computing is adaptation, which is necessary when a mismatch between the supply and demand of a resource occurs. The resource may be wireless bandwidth, energy, computing cycles, memory, et cetera. Moreover, pervasive computing implies context-awareness and requires the least possible intrusion on end user. In other words, it must be cognizant of its users state and surroundings, and must modify its behavior based on this information.

From above, it is clear that pervasive computing, though stemming out from computer science, is of paramount importance in many other fields, like for example wireless communications. In fact, the “anytime anywhere” availability of information and contents of different nature, has become a must for current wireless systems, which meanwhile are requested to hide the underlaying increased complexity to the end user, who wants to perceive technology as more and more easily accessible.

While the “anytime anywhere” concept implies mobility, adaptation is another key issue in wireless systems, where adaptation can be intended at various levels: to the time-variant (and frequency-selective) wireless channel, to the kind of application to be conveyed, to specific user requirements, et cetera. This introduces high dynamicity in the system, which is requested to monitor its “environment”, defined in the widest possible sense as *e.g.*, number and position of users, channel conditions, transmission quality, and to react to the specific situation perceived.

So, in current wireless systems, where different kinds of applications are available while the medium poses specific challenges, static planning of resource distribution and usage is not a sufficient tool any longer, but dynamic functionalities able to cope with the specific status of the system in the specific moment under consideration, are mandatory.

In fact, wireless systems until 2nd Generation (2G) were characterized by hard capacity, *i.e.*, a deterministic number of users could be served by a given Base Station (BS), and only vocal application was supported, meaning that link requirements to be met were only set in terms of block error rate and delay. From 3rd Generation (3G) on, wireless systems have been characterized by a plethora of multimedia applications available to the end user, raising the problem of how the system could efficiently manage the different requirements. In fact, each application type is characterized by specific requirements, which can be set in terms of average bit rate, maximum Bit Error Rate (BER) and, hence, minimum Signal-to-Interference-plus-Noise–Ratio (SINR), maximum delay, et cetera. All these features are usually considered as part of a set of characteristics summarized under the expression "Quality of Service (QoS)", which could be defined as *the set of requirements to be met by the system for a specific application requested by a user.* Due to the application differentiation, also QoS should be handled in a differentiated way. Moreover, the offered traffic continuously changes according to the number of users and the specific mix of applications required, since each user can request different applications. However, at this point it is worth specifying that, commonly, QoS is applied to an end-to-end vision of the system (*i.e.*, it is evaluated in layers above the forth in traditional protocol stack), whereas in this Thesis it is considered and evaluated at link level, since the main focus is on strategies laying at the Medium Access Control (MAC) layer. So, in the dynamic scenario previously described, QoS can not be achieved through an a priori planning procedure, which statically configures the system, but is dynamically pursued by a set of functionalities grouped under the term "Radio Resource Management (RRM)", which is *the set of functionalities whose aim is provide services according to the QoS negotiated for each application over the area covered by the system and optimize system capacity through the choice of the best resource sharing among users* [8] [9] [10] [11] [12]. Scheduling, together with some other well known functionalities such as Power Control (PC), Handover (HO), Admission Control (AC), Congestion and Load Control, and Link Adaptation (LA), belongs to RRM.

In this Thesis RRM for pervasive mobile communication systems will be investigated, and in particular scheduling and radio resource assignment. The pervasiveness will lay in two different aspects that will be investigated separately: from an "architectural" viewpoint, *i.e.*, highlighting the degree of penetration of wireless technology in the environment, and from a "procedural" viewpoint, putting emphasis on the algorithmic sense, as clarified in the following pages.

At first, scheduling was addressed during the Fifties, when American industries decided to use the expertise they gained on operational research for military issues, and applied scheduling with the aim of optimizing industrial logistics. From that point in time on, many applications have been identified ranging from industry [13], [14], to computer science [15], [16], from electronics [17] to telecommunications. Due to this versatility of application, generally speaking scheduling could be defined as *the assignment of a limited set of resources among several activities on the temporal axis according to their deadlines.* Scheduling algorithms are, in general: time-constrained, dependent on the maximum capacity and subject to optimization criteria based on queue length, balanced resource sharing, delivery delay and resource assignment cost. Therefore, it could be interesting to identify when a scheduling algorithm can be defined as *optimum*. Even though it has been proved that in computer science Earliest Deadline First (EDF) is the optimum scheduling strategy for Central Processing Unit (CPU) without energy constraints and in the presence of delay-constrained wired networks [15], [16], the identification of "optimum" scheduling strategies for wireless systems is still an open issue and, even worst, though often scheduling algorithms are claimed to be "optimum" or "robust" [18], [19], [20], [21], [22], it is not clearly defined what "optimum scheduling" stands for (maximizing capacity? Guaranteeing fairness? Finding the best trade-off between both?).

Looking at the history of wireless scheduling, firstly, the classical application-aware scheduling strategies were borrowed from the world of computer science, *e.g.*, EDF and Generalized Processor Sharing (GPS) [23], [24], [25]. Later, many researchers applied channel-aware techniques, identifying the possibility of exploiting channel fluctuations and turning a drawback into a possible advantage. The most important classes of strategies identified with this aim, are based on the concept of Opportunistic Scheduling (OS) [26], which however may rise some fairness problems for users perceiving bad channel quality for long time. Proportional Fair (PF) and Wireless Adapted Fair (WAF) [27], [28] algorithms introduce the additional purpose of guaranteeing fairness among users while exploiting channel variability. However, early studies of these techniques considered non-realistic channel models and simplified traffic assumptions.

So, on one hand some works considered the statistical channel fluctuations through mathematical models, *e.g.*, the Markov chains as in [29] and [30]; on the other hand, a first service differentiation was introduced [25], [31]. However, wireless channel results from different phenomena not always captured by Markov chains, as well as realistic traffics need a large amount of parameters to be modelled.

As already emphasized, mobility and adaptation are mandatory features in pervasive networks. Nevertheless, they are necessary in current wireless systems due to the availability of different applications. Thus, the potentialities of a cross-layer implementation of the scheduling functionality in a packet-based wireless cellular system, *i.e.*, the exploitation of information exchange between even non-adjacent layers of the protocol stack, could lead to significant performance gain. The motivation of this approach is that the service differentiation offered by the systems from 3G on, requires a smart distribution of the radio resources available in the system, scarce by nature, possibly taking into account the different QoS requirements coming from the applications. So, the scheduler has the role of properly selecting the users to be served and mapping the packets on the best possible set of radio resources among the available ones, while taking into account the constraints at the physical layer and the requirements set at the application layer. Different papers in the literature deal with this concept and different definitions have been provided [32]. However, the potential advantages of using cross-layer techniques in scheduling over wireless shared channels are still largely unknown.

In this Thesis, an overview of cross-layer approaches will be provided. Moreover, the formalization of a functional split of scheduling is performed: in multi-user environments scheduling operations become more and more complex as the number of users competing for the wireless shared channel increase. In this case, since fully optimized scheduling could require an infeasible complexity, it may be useful to split it in some steps. In fact, the scheduling functionality provides an answer to these two main questions: who will be the next user to be allocated? Which resources will the user be assigned with? The answer to the first question could be provided working on an abstract concept of radio resource, without knowledge of the specific air interface. On the opposite, for the second answer the knowledge of the particular air interface is compulsory. Although this approach has been already presented in few recent works [33], [34], [35], none of them explicitly defines it as a general framework, and takes into consideration realistic channel and traffic models as well as a cross-layer interaction between physical, data link and higher layers.

Most of the works in the literature deal with Time Division Multiple Access (TDMA) techniques [27] [36] [37]. However, the issue of scheduling realistic traffic over complex shared air interfaces based on multi-carrier techniques, has recently attracted a large interest [38], [39], [40], [41], [42], [43]: MC-CDMA refers to an air interface where radio resources are simultaneously exploited at frequency, time and code division; OFDMA techniques can be seen as a subset of MC-CDMA, and are used in many recent standards, like IEEE802.16 or LTE.

The objective of this Thesis is to design and test scheduling algorithms implemented in pervasive environments, where pervasiveness is investigated from two different (and separated) points of view:

- pervasiveness from the architectural viewpoint, *i.e.*, an innovative network, composed of a set of heterogeneous devices “sensing” a target area and realizing a high degree of penetration in the environment, is investigated;

- pervasiveness from the algorithmic viewpoint, *i.e.*, a cellular system, where completely distributed computing is performed, is investigated.

The first viewpoint is applied to an emergency scenario where pervasiveness is a fundamental characteristic, thus, a hierarchical ad hoc network is deployed. Wireless ad hoc networks attract raising interest in research due to the flexibility of application and deployment they offer. In fact, they support both single- and multi-hop transmission, and energy constraints are not as restrictive as in wireless sensor networks. Moreover, though the classical approach is distributed, wireless ad hoc networks do not prevent from using some centralized functionalities [44].

Many works on resource allocation over wireless ad hoc networks have been published [37], [45], [46], [47], [48], [49]. However, some of them present enhancements of Carrier Sensing Multiple Access with Collision Avoidance (CSMA/CA) like [45] and [46], some others implement a distributed joint power control and channel allocation by means of the graph theory like [47] and [48], and only a few papers consider a cross-layer approach implemented in the scheduler taking into account information coming from non-adjacent layers of the protocol stack like [37], where a centralized algorithm is presented, and [49], where a distributed algorithm is proposed.

In an innovative hierarchical emergency-deployed network, it is of great interest to evaluate the performance of a centralized cross-layer scheduling technique. This will be done in this part of the Thesis via simulation due to the complexity of cross-layer implementation, which makes analytical evaluations prohibitive. Many aspects will be investigated, like algorithm design logic, implementation and complexity, parameter optimization, impact of traffic load, benefits introduced by cross-layer with respect to traditional scheduling strategies.

As already mentioned, only a few papers study cross-layer scheduling strategies taking into account information coming from non-adjacent layers of the protocol stack, *e.g.*, [37] and [49]. However, in all cases perfect Channel State Information (CSI) is assumed at the scheduler.

The novelty introduced is the cross-layer centralized approach applied to realistic traffic with imperfect channel state information. Moreover, the network architecture is innovative, and is characterized by the presence of heterogeneous devices organized in a hierarchical structure and responding to the "opportunistic network" paradigm [50]. In fact, though a centralized cross-layer approach is implemented in [37] in case of IEEE802.16 networks, simplified traffic models and perfect channel information are considered. Moreover, only two papers have been published about scheduling of video traffic over ad hoc networks: [51], which mainly focuses on video transmission optimization through the transport layer and the application level, and [52], where cross-layer scheduling is implemented in wireless mobile ad hoc networks.

Before studying such complex pervasive hierarchical network based on the paradigm of opportunistic networks, cross-layer scheduling over a cellular MC-CDMA system is investigated. In fact, dealing with realistic traffic models over realistic channels with a cross-layer approach is already a challenging task. Moreover, a quantitative evaluation of the benefits introduced by a cross-layer scheduling really tuned on the applications under consideration, with respect to traditional strategies, has not been performed yet. For this reasons, it is worth preliminary investigating cross-layer scheduling in cellular multi-carrier systems.

In such scenario, where the demand for multimedia wireless services is expected to grow substantially as new wireless communication devices are offered on the market, supported by so-called 3G and 4th Generation (4G) mobile networks, it is quite interesting to note that, in order to be up to the challenge, such networks must meet a two-fold, contradictory, demand: first, to provide a smooth and fair, to the extent of the possible, QoS as a user roams from a close-to-center cell location to an edge-of-cell one. Second, the networks must achieve the maximum spectrum efficiency, hence, operate in an environment with maximum reuse of the spectral resource, thereby creating much more severe interference conditions in the cell border area compared with those prevailing closer to the base.

In the past years, several approaches relying on the concept of inter-cell coordination have emerged from the wireless research community, which can be seen as potential solution to this dilemma. It should be distinguished between two categories: packet-based and resource-allocation based coordination. In the first, data packets destined at the users are replicated at several base stations, before jointly precoding/beamforming and transmitting from all the base station antennas [53], [54], [55]. Typically, this approach is the optimal one because it eliminates the notion of cell border in favor of a virtual Multiple Input Multiple Output (MIMO) view of the entire network. The downside is a large overhead in inter-cell signaling, packet routing, and feedback for exchanging the channel state information required to compute the precoders, although some overhead reduction methods are emerging [56]. In the second approach, interference is tackled by means of coordinated resource control, *e.g.*, power, scheduling, et cetera, between the cells [57], which makes lower complexity, distributed coordination techniques possible. Power control, smart soft reuse partitioning are possible strategies there [58], [59], [60].

The use of power control combined with OFDMA user scheduling can be considered as a way to deal with interference, while guaranteeing fairness among users. Traditionally, distributed power control has targeted the maximization of the number of users achieving a prescribed QoS threshold. However, in network design aimed at carrying usual best effort Internet Protocol (IP) traffic, link adaptation protocols exist and maximizing the sum of user rates can be more relevant. Dynamic multi-cell power control targeted at maximizing the sum of user rates in the network is a very difficult task and does not lend itself easily to a distributed implementation across the cells, except some particular cases with a large number of users [61]. The reason is as follows: dynamic power control affects the SINRs of all users in all cells in a fully *coupled* manner making interference unpredictable. Nevertheless, fairness is a relevant issue, since serving only users with best channel conditions does not lend to substantial revenue to operators, who are interested in serving at least with minimum possible QoS the largest possible number of users.

In this scenario, though the system is quite traditional, all the four previously listed characteristics related to pervasiveness are fulfilled.

This Thesis is organized as follows: in Chapter 1 some preliminary necessary definitions are introduced and a detailed state of the art about basic scheduling strategies, especially for multi-carrier based systems, is reported. In Chapter 2 the main characteristics, the structure, and the main advantages of multi-carrier systems is introduced and discussed. In Chapter 3 the main cross-layer approaches used in the literature are presented, then, a functional split of the scheduling module is proposed together with a new cross-layer architecture. In Chapter 4 a cross-layer strategy previously published for TDMA systems has been adapted to MC-CDMA systems and, then, another one with reduced complexity is introduced. Performance over a cellular system characterized by realistic features are evaluated. In Chapter 5, the new cross-layer strategy is applied, optimized for and tested on an original innovative multi-carrier ad hoc network. In Chapter 6 a distributed approach to scheduling over a multi-cell OFDMA-based network through the introduction of the power planning concept is presented. Finally, a discussion on results obtained and open issues is performed.

Ideas and results flowed in this Thesis have been generated and maturated thanks to the discussions and exchanges had in the framework of some European Projects, where many collaborations have been performed. In particular, the state of the art is part of a work performed in NEWCOM++, the Network of Excellence in Wireless COMmunication funded by FP7, and specifically in WPR.8. Results related to cross-layer scheduling over multi-carrier cellular systems have been obtained through a collaboration with the Technical University of Munich, and in particular with Dr. Guenther Liebl and Timo Mayer, and the University of Ferrara, with Prof. Velio Tralli, inside NEWCOM, the Network of Excellence in Wireless COMmunication funded by FP6, and in particular its Dept. 7. Results related to distributed scheduling over multi-carrier multi-cell systems with power planning have been obtained through a collaboration with Institut Eurecom, where six months have been spent under the supervision of Prof. David Gesbert. Also this activity has been performed inside WPR.8 of NEWCOM++. Moreover, some results have contributed to OPTIMIX, Optimisation of Multimedia over wireless IP links via X-layer design, a Specific Targetted Research Project funded by FP7. Finally, many parts of this Thesis are the outcome of discussions held in the context of the COST Action 2100 on Pervasive

Mobile and Ambient Wireless Communications, where at each meeting held every four months since December 2006, temporary results obtained on ongoing works have been presented and fruitfully discussed with scientists participating in the Action. Among the many who contribute with objections, suggestions and contributions, a special mention goes to Dr. Wolfgang Karner, from the Technical University of Wien, with whom a collaboration has been also taken.

As a final remark, part of the results reported in this Thesis, have been also published on international journals and conferences. Some others have been disseminated and discussed during presentations of temporary documents at COST Action 2100 meetings. Others have contributed to European Project Deliverables.

In the following, the complete list of publications performed during the PhD is reported, according to the category each one belongs to.

Journal Publications

- *Cross Layer Radio Resource Allocation for Multi Carrier Air Interfaces, in Multi-Cell Multi-User Environments*, V. Corvino, V. Tralli, R. Verdone, to appear on IEEE Transaction on Vehicular Technology; also TD(07)300 presented at the 3rd Management Committee Meeting of COST Action 2100, Duisburg, Sept. 10th-12th, 2007.

- *Cross-Layer Scheduling over a Heterogeneous Opportunistic Emergency-Deployed Wireless Network*, V. Corvino, A. Carniani, V. Tralli, R. Verdone, to appear on the International Journal of Wireless and Mobile Computing, also TD(08)674 presented at the 6th Management Committee Meeting of COST Action 2100, Lille, Oct. 6th-8th, 2008.

Conference Publications

- *A Hierarchical Hybrid Network Model*, R. Verdone, V. Corvino, J. Orriss, presented at 3G and Beyond 2005 - Sixth IEE International Conference on 3G and Beyond Mobile Communication Technologies, London, Sept. 7th-9th, 2005.

- *Buffer Management and Scheduling Strategies for Heterogeneous Traffic including Video Streaming in a MC-CDMA System*, V. Corvino, G. Liebl, T. Mayer, V. Tralli, R. Verdone, presented at Workshop on Trends in Radio Resource Management - 2nd Edition, Barcelona, Nov. 16th, 2005.

- *Scheduling of Mixed Traffic over MC-CDMA under Varying Load and Channel Conditions*, V. Corvino, G. Liebl, L. Giuliani, V. Tralli, T. Mayer, R. Verdone, presented at IEEE ISWCS 06 - 3rd International Symposium on Wireless Communication Systems, Valencia, Sept. 5th-8th, 2006; also TD(07)201 presented at the 2nd Management Committee Meeting of COST Action 2100, Lisbon, Feb. 26th-28th, 2007.

- *Advanced Transmission Strategies for Mixed Traffic over MC-CDMA*, G. Liebl, V. Corvino, L. Giuliani, V. Tralli, T. Mayer, R. Verdone, presented at NEWCOM-ACoRN Joint Workshop, Wien, Sept. 20th - 22nd, 2006.

- *D08. Simulator for Evaluating Advanced Scheduling Techniques Based on a Cross-Layer Approach*, V. Corvino, G. Liebl, V. Tralli, T. Mayer, R. Verdone, Technical Demonstration presented at the NEWCOM Dissemination Day, Paris, Feb. 15th, 2007. (Demo)

- *Cross-Layer Resource Allocation for MC-CDMA*, V. Corvino, V. Tralli, R. Verdone, presented at IEEE ISWCS 07 - 4th International Symposium on Wireless Communication Systems, Trondheim, Oct. 16th-19th, 2007.

- *Cross-Layer Scheduling for Multiple Video Streams over a Hierarchical Emergency-Deployed Network*, V. Corvino, V. Tralli, R. Verdone, presented at WiMAN 2008 - the Second IEEE International Workshop on Wireless Mesh and Ad Hoc Networks, Beijing, China, June 20th, 2008; also TD(08)401 presented at the 4th Management Committee Meeting of COST Action 2100, Wroclaw, Febr. 6th-8th, 2008.

- *A Novel Distributed Interference Mitigation Technique using Power Planning*, V. Corvino, D. Gesbert, R. Verdone, presented at IEEE WCNC 2009, Budapest, April 5th-8th, 2009, also TD(09)706 presented at the 7th Management Committee Meeting of COST Action 2100, Braunschweig, Feb. 16th-18th, 2009.

- *A Novel Distributed Interference Mitigation Technique using Power Planning*, V. Corvino, D. Gesbert, R. Verdone, presented at the NEWCOM++ Dissemination Day, Barcelona, March 30th-April 1st, 2009. (poster)

- *A Novel Distributed Interference Mitigation Technique using Power Planning*, V. Corvino, D. Gesbert, R. Verdone, presented at the NEWCOM/ACoRN Worskhop, Barcelona, on March 30th-April 1st, 2009.

Temporary Documents

- *TD(08)475 - Error Prediction Based Frequency Selection in MC-CDMA Systems Resource Allocation*, V. Corvino, W. Karner, R. Verdone, presented at the

4th Management Committee Meeting of COST Action 2100, Wroclaw, Febr. 6th-8th, 2008.

- *TD(08)527 - Cross-Layer Scheduling over a Hierarchical Heterogeneous Emergency-Deployed Network*, V. Corvino, A.Carniani, R. Verdone, presented at the 5th Management Committee Meeting of COST Action 2100, Trondheim, June 4th-6th, 2008.

Project Deliverables

- *DR7.2 - First report on common framework/models and activities in Dept. 7*, deliverable for NEWCOM Dept. 7, edited by R. Agusti and J. Perez-Romero, delivered on May 31st, 2005.
- *DR7.3 - Recommendations for the reference scenarios to be dened in E-MORANS and for the Knowledge Networking DB*, deliverable for NEWCOM Dept. 7, edited by L. Ferreira, delivered on February 28th, 2006.
- *DR7.4 - Final Report on the activities carried out in Dept. 7*, deliverable for NEWCOM Dept. 7, edited by J. Perez-Romero, delivered on February 28th, 2007.
- *DR8.1 - State of the Art on scheduling techniques for the wireless channel and the design of algorithms*, deliverable for NEWCOM++ WPR.8, edited by V. Corvino, delivered on June 27th, 2008.
- *DR9.1 - Identification of relevant scenarios, use cases and initial studies on JRRM and ASM strategies*, deliverable for NEWCOM++ WPR.9, edited by A. Serrador, delivered on January 10th, 2009.

- *D1.2 - OPTIMIX requirements document*, deliverable for OPTIMIX, edited by Thales, delivered on May 30th, 2008.
- *D1.3 - OPTIMIX specifications*, deliverable for OPTIMIX, edited by Thales, delivered on September 2nd, 2008.
- *D2.3A - Preliminary scheme of JSCC/D controller for point to multipoint communication and optimization criteria*, deliverable for OPTIMIX, edited by CNIT, delivered on January 30th, 2009.
- *D3.3A - Specification and preliminary design of data link layer*, deliverable for OPTIMIX, edited by VTT, delivered on January 30th, 2009.

Chapter 1

Scheduling and Resource Allocation: State of the Art

In this Chapter an overview of the main scheduling techniques for multi-carrier based systems published in the literature will be provided. Clearly there is no pretension of completeness, since over the last fifteen years hundreds of papers have been published on this topic. Trying to find a way to group them is not easy, since most of them are designed according to different heuristics, refer to different systems, *i.e.*, air interfaces, support different applications, implement different approaches, use different evaluation metrics. However, since many algorithms are heuristic adaptations or simplifications of a few commonly agreed approaches, *e.g.*, optimization problem or game theory, in this Chapter these basic approaches will be identified and described.

Algorithms will be grouped according to the fact that they have been specifically designed for cellular, distributed, or heterogeneous networks, since all these architectures will be considered in the rest of the Thesis. It could be noticed that the State of the Art (SoA) related to multi-carrier based cellular systems is larger than those related to distributed and heterogeneous networks. This should be expected since, as it will be clarified later, the literature on scheduling for cellular systems is more mature, whereas literature about distributed and heterogeneous networks are still in an embryonic stage [62]. However, a detailed survey of scheduling algorithms classified according to the aim they pursue, *e.g.*, throughput maximization, fairness guarantee, etc., is provided. From the analysis of the literature, it will emerge that generally most of the approaches proposed are heuristic methods used to define new scheduling policies, whereas only a few works consider analytic frameworks, typically according to game theory or optimization methods based on utility functions. Anyway, before entering the topic, some useful definitions will be introduced.

1.1 Some Preliminary Definitions

Many definitions for "scheduling" in wireless systems have been provided over the last fifteen years. For example, in books related to 3G systems, definitions such as "the packet scheduling function shares the available air interface capacity between packet users. The packet scheduler can decide the allocated bit rates and the length of the allocation" according to [63], or, "the main task of the PS (*note:* Packet Scheduling) is to handle all NRT (*note*: Non Real Time) traffic, *i.e.*, allocate optimum bit rates and schedule transmission of the packet data, keeping the required QoS (*note*: Quality of Service) in terms of throughput and delay" [64], are provided. Trying to generalize to abstract a unique definition, scheduling could be defined as a *RRM functionality performed at the MAC sublayer, whose aim is to evaluate the set of resources available and distribute them among competing flows according to their priority in order to guarantee the QoS negotiated by flow and network*, where a flow can be defined as one of the possibly several parallel data streams supported by a certain user.

Since in the abovementioned definition the term “resource” is introduced, it would be worth trying to specify what a resource is in the peculiar contest of wireless systems, especially considering that a plethora of them (*e.g.*, mobile telephony, mobile data access, portable communications, etc.) are offered to the end user and possibly coexist. However, formalizing a general definition of “*radio resource*” is quite hard, since scheduling definition is provided regardless of the type of system over which it is performed (in fact, as shown in the Introduction, it applies to several disciplines) and should be applied to any kind of wireless systems and, hence, to any kind of air interface. In order to generalize this concept, a Radio Resource (RR) could be defined as *the signal format necessary to define how a certain amount of data can be transmitted over the wireless medium.* According to this definition, a specific RR is fully identified by a set of different “dimensions” which vary from air interface to air interface. For example, in a TDMA system, an RR is identified by all the following dimensions: the time slot over which transmission is allowed, the carrier frequency and the relevant bandwidth, the modulation and coding format, the power level and possibly the transmitting spatial dimension.

According to the definition of RR previously provided, a Resource Unit (RU) can be consequently defined as the smallest RR assignable or, alternatively, the RR allowing the minimum amount of data to be transmitted. However, since a RR (and consequently a RU) might be composed of both discrete (*e.g.*, time slot) and continuous dimensions (*e.g.*, power level), it is sometimes useful to define a numerable set of resources offered by a certain system. Thus, it is a common practice also to use a “reduced” definition of resource intended as the set of only discrete dimensions, and in particular the frequency carrier, the time slot, and the coding sequence in case of

Code Division Multiple Access (CDMA) based systems, and the transmitting beam or antenna in case of Space Division Multiple Access (SDMA). In such situation, it is indeed possible to compute the maximum number of resources offered by the system. According to this definition, the problem of scheduling is about the distribution of orthogonal resources among competing users, where the orthogonality implies that each resource can be allocated to at most one user. From now on, the term Radio Resource will be used both in its fully comprehensive sense and in the reduced one according to the context.

Having defined the RR, it is now possible to introduce the concept of Adaptive Radio Resource Assignment, as *the allocation of a specific set of radio resources to a certain flow according to the contingent state of the system.* This definition has two main implications: firstly, when performing RR assignment, the air interface structure of the system under investigation is known and considered in the process, since it defines the specific format of RRs; secondly, the adaptiveness of the process can be related to one or several time-varying characteristics of the system, such as the wireless channel, the state of the queues, the number of users, the QoS requirements, the state of some layers in the protocol stack, et cetera. In Fig. 1.1 a graphical representation of the scheduling and radio resource allocation functionalities in terms of inputs and outputs is reported. It is also emphasized how scheduling decision depends also on the specific objective pursued by the policy under consideration, which in turn determines the most suitable method and tool to be used to perform such functionalities.

In the literature, the terms “scheduling” and “resource assignment” are often used as synonyms, or interchangeably without a real (or at least clear) distinction.

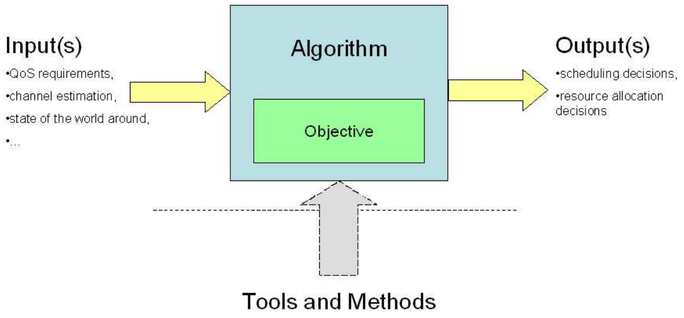

Figure 1.1: Graphical representation of scheduling algorithm design.

However, according to the definitions provided, it is evident that while scheduling implies resource assignment, the contrary does not hold. In fact the temporal axis and the multiuser dimension are not present in the second, where only instantaneous conditions related to a single user are considered. Only a few works in the literature formalize this distinction, whose potential is high for future wireless systems, as discussed below.

Over the last fifteen years, wireless systems have become more and more complex; consequently, also scheduling complexity has increased. So, some works in the literature [35], [65], [66], presented a functional split of the whole scheduling process: it can be imagined that the identification of the flows selected for transmission and of the relevant RRs to be allocated, could be performed in different stages, in order to reduce complexity. According to this definition, it could be noticed that the module responsible for radio resource assignment should obviously be aware of the air interface, since the knowledge of the particular set of resources (frequencies, slots, codes, maximum power allowed, modulation and coding format, etc.) offered to the system and, possibly, of the channel quality perceived by the users, are needed. On the contrary, the scheduling module could be even air interface-unaware, since the decision on the particular flow to be served could depend much more on some application-side information, such as the state of the buffers or some application-specific requirements. In such a scenario, the knowledge of the air interface structure and of channel dynamicity at the resource assignment module, and of application parameters at the scheduler, allow the real implementation of a cross-layer approach, which is emerging as a hot topic about scheduling for a valuable QoS management. For instance, in [62] the authors present resource allocation as a cross-layer design based on an optimization of MAC layer parameters with an accurate model of the Physical (PHY) layer.

Since, as already discussed, emerging wireless systems seem to be Multi-Carrier (MC) based, an overview of the scheduling strategies designed for such kind of air interface will be provided. Then, even though usually scheduling is addressed in cellular systems, where a centralized unit takes decisions according to the information collected about each flow, nowadays new scenarios where nodes are organized in an infrastructure-less fashion (such as mesh, ad hoc and sensor/actuator networks) are emerging. In this case, the main issue is the selection of the nodes allowed to transmit and the relevant resources without the help of a centralized "omniscient" controller and, hence, where at each node only partial information about the rest of the network is available. Thus, a survey of the few strategies already present in the literature for such scenarios will be provided. Finally, another important issue is the coexistence of several systems which can be simultaneously available to a given user and where it could be beneficial for the user himself to exploit the diversity and the larger capacity offered by the multiple air interfaces available. Also the literature related to this system structure will be analyzed.

1.2 From 2G to 3G: from Planning to Managing

The convergence between mobile and data access internet-based services posed specific challenges to wireless networks designers about how to exploit the set of resources available as efficiently as possible. In fact, since until 2G the only application supported was voice, RRM was not crucial, whereas network planning had a fundamental role. Thus, in such system the conventional approach used was "divide and conquer" based, with the following meaning:

- in the "divide" phase, network resource planning was applied to fragment the network area into smaller zones isolated from each other from an electromagnetic point of view. In cellular systems, the cluster concept was introduced, defined as *the set of cells over which the whole resource budget is used*, and for a given cluster a certain radio resource could be used only once. In ad hoc networks, isolation of transmit-receive pairs from each other was performed by means of carrier sensing based MAC protocols;
- in the "conquer" phase, the loss of link efficiency due to interference for a given cell (or for a local transmit-receive pair in ad hoc networks) was compensated via the introduction of specific techniques such as efficient Forward Error Correction (FEC) coding, fast LA protocols, multiple-antenna transceivers [67] and channel-aware scheduling strategies [68].

However, the need for high spectral efficiency led system designers towards an aggressive spectral reuse, giving an increased interference in the network in spite of power control and dynamic resource allocation. Moreover, multi-cell resource planning and power control were traditionally designed to reach a SINR target simultaneously for all interfering terminals, aiming at allowing users to operate under a common minimum Carrier-to-Interference (C/I) level, defined according to the receiver's sensitivity or a preset operating point at the user terminals (access points). This SINR balancing approach ensured the worst-case outage probability necessary for connection-oriented voice calls [59], [69], [70].

Nowadays, the concept of a specific operating point is becoming less relevant and network planning phase has no sense without RRM, since modern networks are supposed to support and manage different QoS requirements in the presence of mixed traffic composed of possibly Real Time (RT) and Non-Real Time (NRT) applications. This should be done taking into account the intrinsic time-varying and frequency-selective nature of the wireless channel, which results in highly bursty errors, time-varying capacity and different throughput and delay values experienced by each user within the system, according to the currently perceived channel quality. For these reasons, it is clear that, while fulfilling QoS requirements, scheduling should also maximize system usage and, thus, the aggregated throughput, while trying to guarantee some fairness among differently located users. Moreover, current systems typically feature Adaptive Modulation and Coding (AMC) schemes, aiming at maximizing the sum network capacity, defined as the sum of simultaneous transmit-receive link capacities, which appears as a meaningful metric. Due to the issues abovementioned, the limitation of the divide and conquer approach applied to network-wide performance optimization is clear.

So the first idea explored by researchers dealing with wireless scheduling was the exploitation of channel variability through the so called **opportunistic scheduling** [26]. The aim of such algorithm is the maximization of system throughput by serving always the user(s) with the best channel conditions, realizing the so called "multiuser diversity" [71], *i.e.*, *the independence of random channel fluctuations experienced by each user in the system.* However, it is worth noting that this gain can be realized only if link adaptation techniques are available to take advantage of the improvement in channel conditions. This technique has the advantage of maximizing throughput and spectral efficiency, which is crucial in wireless systems due to spectrum scarcity, but it has an important drawback in its unfairness, since users affected by poor channel conditions may starve for long time. Currently, some works [22] have been carried out in order to incorporate QoS constraints into opportunistic schedulers; thus, trading off multiuser diversity and user satisfaction.

In order to provide **fairness** among users, in [72] it was shown that this can be at least partially restored by modifying the scheduling criteria in one of several possible manners. Many new algorithms were proposed, and they can be grouped into two categories. The main algorithm which could be recognized in the first category is: the PF scheduling [73] [74] [75], whose aim is maximizing throughput provided that long term fairness is guaranteed. Strategies like Max – Min Fairness, Weighted Max – Min Fairness, Purely Fair Scheduling, WAF scheduling, could be considered as enhanced versions of PF scheduling. The second category is based on the concept of leading and lagging flows, where "lead" is defined as *the amount of service that a flow, having experienced good channel quality until the current instant, should release in* *favor of "unlucky" users*, whereas "lag" is *the amount of service a flow should receive due to the fact that it has experienced bad channel quality until the current instant.* Obviously, a flow could be either leading or lagging, not both simultaneously. The main strategies based on this approach are the following: Wireless Fair Service (WFS) [76], Idealized Wireless Fair Queuing (IWFQ) [77], Channel condition Independent Fair Queuing (CIF – Q) [78], Server Based Fairness Approach (SBFA) [79]. However, also these strategies suffer from some important limitations: in particular, they do not support short term fairness, since transmission is always subject to good channel conditions, they are based on very simplified channel quality evaluations such as "*good*" and "*bad*", leading users may be affected by ungraceful service degradation since they can be excluded from transmission for long time, which is critical in case of RT applications.

The two large categories presented above, which could respectively be defined as "*totalitarian*" and "*egalitarian*" as well identified in [80], were initially applied to TDMA air interfaces and in the presence of simplified traffic models such as buffers always full, no delay requirements, no service differentiation, et cetera. Moreover they considered ideal channel knowledge, which is an unrealistic assumption due to the channel random behavior and could lead to bad performance when implemented in real systems. So, a step further was performed in order to consider the incompleteness of channel knowledge. For example, in [29] [30] [81] some probabilistic models where used to introduce and manage channel variability, even though most of them are based on Markov chains, which were proven to be not satisfactory for channel modelling [82].

1.3 The Advent of Multi-Carrier Based Systems

More recently, service differentiation in advanced communication systems has been identified as a relevant issue to be addressed. So, different more complex statistics were introduced to take into account the different behavior of multimedia traffic sources [31], [37], [81], and more complex air interfaces, which could be multi-carrier and possibly MIMO based [34], [35], [65], [83], were considered. In particular, OFDMA has been indicated as the candidate access technology for future wireless systems such as WiMAX [84] and Universal Mobile Telecommunication System (UMTS) LTE [85], due to some interesting properties such as wideband communications, flexibility in allocation and supportable bit rates, robustness against interference and frequency selective fading, high spectral efficiency, ease of implementation [86] and, especially for scheduling, multiuser diversity, *i.e.*, the capacity of exploiting the channel fluctuations observed by more than one user in the allocation process. Moreover, cross-layer implementation of scheduling functionality is raising more and more interest, since the exploitation of information coming also from non adjacent layers of the protocol stack (*e.g.*, the application layer) could be beneficial when selecting which user should be allowed to transmit [34], [37], [65].

There are a number of different ways to take advantage of multiuser diversity in OFDMA systems. The idea is to develop algorithms to determine which users to schedule, how to allocate subcarriers to them, and how to determine the appropriate power levels for each user on each subcarrier. Referring to a downlink OFDMA system, usually users estimate and feedback the CSI to their base station, where subcarrier and power allocation is determined according to users' CSI and resource allocation procedure. Once the subcarriers for each user have been determined, the base station must inform each user about which subcarriers he has been allocated with. This subcarrier mapping must be broadcast to all users whenever the resource allocation changes. Typically, resource allocation must be performed with timing on the order of the channel coherence time, although it may be performed more frequently if there are many users competing for resources. Resource allocation is usually formulated as a constrained optimization problem, to either:

- minimize the total transmit power with a constraint on the user data rate [87], [88],
- maximize the total data rate with a constraint on total transmit power [41], [89], [90], [91],

where the first objective is appropriate for fixed-rate applications (*e.g.*, voice), while the second is more appropriate for bursty applications like data and other IP based services.

1.3.1 Basic Scheduling Techniques

Over the last years many works have been published about scheduling in multi-carrier based systems. However, since these are typically cellular wireless systems, many of the algorithms published are extensions of strategies designed for TDMA based systems.

Maximum Sum Rate Algorithm

The objective of the Maximum Sum Rate (MSR) algorithm is to maximize the sum rate of all users, given a total transmit power constraint [41]. This algorithm is optimal if the goal is to get as much data as possible through the system. The drawback of the MSR algorithm is that it is likely that a few users that are close to the base station, having excellent channels, will be allocated with all the system resources. The SINR for user k in subcarrier l can be expressed as:

$$SINR_{k,l} = \frac{\frac{P_{k,l}}{L_{k,l}}}{\sum_{j=1,j\neq k}^{K} \frac{P_{j,l}}{L_{j,l}} + N\frac{BW}{N_{sc}}}, \tag{1.3.1}$$

where $P_{k,l}$ denotes the transmitted power of the l-th subcarrier to the k-th user, $L_{k,l}$ is the related pathloss, N is the noise power over the whole frequency Bandwidth (BW) and N_{sc} is the total number of subcarriers. Based on the Shannon capacity formula, the MSR algorithm maximizes the quantity:

$$\max\left\{\sum_{k=1}^{K}\sum_{l=1}^{L}\frac{BW}{N_{sc}}\left(1+SINR_{k,l}\right)\right\} \tag{1.3.2}$$

subject to

$$\sum_{k=1}^{K}\sum_{l=1}^{L} P_{k,l} \leq P_{max}. \tag{1.3.3}$$

The sum capacity is maximized if the total throughput in each subcarrier is maximized. Hence, the max sum capacity optimization problem can be decoupled into N_{sc} simpler problems, one for each subcarrier. Further, the sum capacity in subcarrier l, denoted as C_l, can be written as:

$$C_l = \sum_{k=1}^{K} \log\left(1 + \frac{P_{k,l}}{P_{max,l} - P_{k,l} + N \cdot L_{k,l} \cdot \frac{BW}{N_{sc}}}\right), \tag{1.3.4}$$

where the difference $P_{max,l} - P_{k,l}$ denotes other users' interference to user k in subcarrier l. It is easy to show that C_l is maximized when all available power $P_{max,l}$ is assigned to just the single user with the largest channel gain in subcarrier l. This result agrees with intuition: giving each channel to the user with the best gain in that channel. This is sometimes referred to as a “greedy” optimization. The optimal power allocation proceeds by the waterfilling algorithm, and the total sum capacity is readily determined by adding up the rate on each subcarrier.

Minimum Transmit Power Algorithm

Another possible approach is to assign resources with the goal of minimizing the overall transmitted power in the system under different rate constraints for each user [92], [93]. This approach can be easily formulated as a Linear Programming (LP) problem, under the assumption that the perceived SINR for each user is known when performing allocation. As for the MSR algorithm, the feasibility of this approach depends on the accuracy of the SINR measurements and is hardly feasible in fast fading environments.

Maximum Fairness Algorithm

Although the total throughput is maximized by the MSR algorithm, in a cellular system like WiMAX, where the pathloss attenuation will vary by several orders of magnitude between users, some of them could be extremely underserved by an MSR-based scheduling procedure. At the opposite extreme, the maximum fairness algorithm [94] aims at allocating subcarriers and power in such a way that the *minimum* user’s data rate is maximized. This essentially corresponds to equalizing the data rates of all users, hence the name “Maximum Fairness”. The maximum fairness algorithm can be referred to as a *Max-Min* problem. The optimum subcarrier and power allocation is considerably more difficult to determine than in the MSR case because the objective function is not concave and, in particular, it is a Nondeterministic Polynomial-time (NP)-hard problem to simultaneously find the optimum subcarrier and power allocation. Therefore, low-complexity suboptimal algorithms are necessary, where subcarrier and power allocation are done separately.

A common approach is to assume initially that equal power is allocated to each subcarrier, and then to iteratively assign each available subcarrier to a low-rate user with the best channel on it [94], [95]. Once this generally suboptimal subcarrier allocation is completed, an optimum power allocation according to waterfilling can be performed. It is typical for this suboptimal approximation to be very close to the performance obtained with an exhaustive search for the best joint subcarrier-power allocation, both in terms of fairness achieved and total throughput.

Proportional Rate Constraints Algorithm

A weakness of the Maximum Fairness algorithm is that the rate distribution among users is not flexible. Further, the total throughput is largely limited by the user with the worst SINR, as most of the resources are allocated to that user, which is clearly suboptimal. In a wireless broadband network, it is likely that different users require application-specific data rates that vary substantially. A generalization of the Maximum Fairness algorithm is the Proportional Rate Constraints (PRC) algorithm, whose objective is to maximize the sum throughput, with the additional constraint that each user's data rate is proportional to a set of predetermined system parameters $\{\beta_k\}_{k=1}^{K}$.

Mathematically, the proportional data rates constraint can be expressed as:

$$\frac{R_1}{\beta_1} = \frac{R_2}{\beta_2} = \ldots = \frac{R_K}{\beta_K}, \tag{1.3.5}$$

where the k-th user's achieved data rate is equal to:

$$R_k = \sum_{i=1}^{N_{sc}} \frac{a_{i,k}}{N_{sc}} \log \left[1 + \frac{\frac{P_{k,l}}{L_{k,l}}}{N \frac{BW}{N_{sc}}} \right], \tag{1.3.6}$$

where $a_{i,k}$ is equal to 1 when the subcarrier is used by the k-th user and equal to 0 otherwise. Clearly, this is the same setup as the Maximum Fairness algorithm if $\beta_k = 1, \forall k$. The advantage is that any arbitrary data rate can be achieved by varying the $\{\beta_k\}_{k=1}^{K}$ values.

The PRC optimization problem is also generally very difficult to solve directly, since it involves both continuous variables $P_{k,l}$ and binary variables $a_{i,k}$, and the feasible set is not convex. As for the Maximum Fairness case, the prudent approach is to separate the subcarrier and power allocation procedure and settle a near-optimal subcarrier and power allocation that can be achieved with manageable complexity. A low-complexity implementation is developed in [95], and the near optimal approach is derived and outlined in [96] and [97].

Proportional Fair Scheduling

The three algorithms discussed so far attempt to *instantaneously* achieve an objective such as the total sum throughput (MSR algorithm), equal data rates amongst all users (Maximum Fairness), or preset proportional rates for each user. Alternatively, one could attempt to achieve such objectives over time, which provides significant additional flexibility to the scheduling algorithms. In this case, in addition to throughput and fairness, a third element enters the trade-off, which is *latency*. In an extreme case of latency tolerance, the scheduler could simply wait for the user to get close to the base station before transmitting. In fact, the MSR algorithm achieves both fairness *and* maximum throughput if the users are assumed to have the same average channels in the long term (on the order of minutes, hours, or more), and there is no constraint with regards to latency. Since latencies even on the order of seconds are generally unacceptable, scheduling algorithms that balance latency and throughput and achieve some degree of fairness are needed. The most popular framework for this type of scheduling is PF scheduling [74], [76].

The PF scheduler is designed to take advantage of multiuser diversity, while maintaining comparable long term throughput for all users. Let $R_k(t)$ denotes the instantaneous data rate that user k can achieve at time t, and $T_k(t)$ be the average throughput for user k up to time slot t. The proportional fairness scheduler selects the user, denoted as k^* with the highest $R_k(t)/T_k(t)$ for transmission. In the long term, this is equivalent to selecting the user with the highest instantaneous rate relative to its mean rate. The average throughput $T_k(t)$ for all users is then updated according to:

$$T_k\left(t+1\right)=\left\{\begin{array}{l}\left(1-\frac{1}{t_c}\right)T_k\left(t\right)+\frac{1}{t_c}R_k\left(t\right),k=k^*\\\left(1-\frac{1}{t_c}\right)T_k\left(t\right),k\neq k^*\end{array}\right. . \tag{1.3.7}$$

Since the proportional fairness scheduler selects the user with the largest instantaneous data rate relative to its average throughput, "*bad*" channels for each user are unlikely to be selected. On the other hand, users that have been consistently underserved receive scheduling priority, which promotes fairness. Parameter t_c controls the latency of the system. If t_c is large, then the latency increases, with the benefit of higher sum throughput. If t_c is small, the latency decreases since the average throughout values change more quickly, at the expense of sum throughput. The proportional fairness scheduler has been widely adopted in packet data systems such as High Speed Downlink Packet Access (HSDPA) and 1xEV-DO, where t_c is commonly set between 10 and 20. One interesting property of PF scheduling is that as $t_c \rightarrow \infty$, the sum of the logs of the user data rates is maximized. That is, PF scheduling maximizes $\sum_{k=1}^{K} \log\left(T_k\right)$.

Although the PF scheduler was originally designed for a single channel time-slotted system, it can be adapted to an OFDMA system. In an OFDMA system, due to the multiple parallel subcarriers in the frequency domain, multiple users can transmit on different subcarriers simultaneously, thus, the original PF algorithm can be extended to OFDMA by treating each subcarrier independently. Let $R_k(t,n)$ be the supportable data rate for user k in subcarrier n at time slot t. Then for each subcarrier, the user with the largest $R_k(t,n)/T_k(t)$ is selected for transmission. Let $\Omega_k(t)$ denote the set of subcarriers in which user k is scheduled for transmission at time slot t, then the average user throughput is updated as:

$$T_k\left(t+1\right) = \left(1 - \frac{1}{t_c}\right) T_k\left(t\right) + \frac{1}{t_c} \sum_{n \in \Omega_k(t)} R_k\left(t,n\right), \tag{1.3.8}$$

for $k = 1, 2, \ldots, K$. Other weighted adaptations and evolutions of PF scheduling for OFDMA are also possible.

With the same principle, extending these commented strategies to systems with multiple transmit and receive antennas, *i.e.*, MIMO-OFDMA, is straightforward, however, since this kind of systems are out of the scope of this Thesis, they will not be considered further.

As a first comment on scheduling techniques published in the literature, it can be noticed that most of the works are based on heuristic methods: each work proposes algorithms designed according to reasonable considerations trying to take into account as many characteristics as possible, but they are usually elaborations/extensions of the basic ideas presented above. Only a few papers try to use theoretical frameworks for the definition of scheduling techniques, mainly because they are too complex to be handled in a few milliseconds. In this case, the most used strategies are based on optimization through utility functions [81], [98], [99], and tools borrowed by economics, such as game theory [58], [100], and auction-based algorithms [101], [102].

1.4 From Single-Cell to Multi-Cell Scenarios: Controlled and Distributed Approaches

All the strategies abovementioned were designed to be implemented as a centralized functionality to be performed at the Base Station Controller (BSC) in 2G systems and in the Radio Network Controller (RNC) in 3G systems, or at the BS. So, many of the scheduling algorithms published in the literature implement a *centralized* approach.

Due to the implementation in more recent systems such as High Speed Packet Access (HSPA) and LTE of fast scheduling (in the order of very few milliseconds) and LA, scheduling function has been moved in Node-B directly. However, while the centralized approach is optimal from the single-cell point of view, since some kind of “god” aware of everything happening inside his cell can take decisions in the best possible way, this could be not true in a multi-cell environment. In fact if every cell takes decisions autonomously, it is possible that problems with intercell interference rise. In this case, it could be beneficial to implement a **coordinated** approach among the different Nodes-B, in order to perform a joint optimization of resources in all cells simultaneously, thus keeping interference in the network under control. This could be achieved through the introduction of a central control unit able to gather information from and coordinate several cells. Joint multi-cell resource allocation offers an enormous number of degrees of freedom governed by the number of cells, times the number of users, times the number of possible scheduling slots, codes, power levels et cetera [57].

Obviously, the potential in coordinated resource allocation across cells also results in several practical issues such as slot level synchronization for large network areas, which can be partly alleviated by clustering the optimization, and joint processing of traffic and channel quality parameters feeded back by all network nodes to a central control unit, leading to request of high computational power and huge signaling overhead.

Even though global network coordination is hard to realize in practice, some recently published and promising methods showed how some multi-cell coordination gain may be realized with limited complexity and/or limited centralized control [60], [103], [104], [105], [106], [107], [108]. In particular, three leading and independent strategies may be identified in the literature toward making multi-cell resource coordination more practical, and they will be described in the following.

Since one of the major difficulties related to interference avoidance is the lack of predictability of interference coming from other links due to the burstyness of traffic and the temporal channel variability, *structuring* could be a good approach to be enforced on the resource planning grid to make interference more predictable. In [103] and [104], a particular power shaping of the time frame in the joint user scheduling and power allocation problem was exploited: the Access Point (AP) transmits with different powers in different portions of the frame, and users are allotted slots according to the amount of interference they can tolerate given their channel conditions. Analogously, in [60] Time-Slot Resource Partitioning is proposed, according to which power shaping over the cell sectors is implemented by turning off sector beams according to a determined sequence. In another approach, structure may be enforced by fixing the order in which time/frequency slots are being filled up with user packets. For underloaded systems, a predictable average portion of the slots remain unused and the location of such slots on the multi-cell resource grid can be optimized to reduce interference for selected users [105]. As shown in [106], the spatial position of users in the cell can also be used to coordinate intercell transmissions to avoid excessive interference. Such clever resource planning schemes are interesting since they offer additional flexibility in mitigating interference with very low complexity and little need for signaling, but they are not fully exploiting the degrees of freedom provided by the joint multi-cell resource allocation problem, as the imposed structure tends to reduce the dimensions offered in the optimization.

Since certain quantities in the resource allocation problem may be continuous, a potentially interesting tool consists of *discretization* of the optimization space, to reduce the number of potential solutions and also to reduce the feedback rate needed to communicate overhead data between nodes. For instance, when the spatial dimension is used, so far, the discretization of the optimal beamforming weights through the use of vector precoding has been proposed mostly for the single-cell scenario for the purpose of feedback reduction as in [107]. In the case of beamforming weights, discretization can be applied posterior to beamforming weight computation. In the case of power control, discretization can be carried out prior to optimization, to simplify the power level search procedure. Remarkably, the discretization of power control, even to its extreme of binary on/off control, can be shown to yield quasi-optimal results in a number of cases [108].

Due to the non-convexity of many of the multi-cell resource optimization problems, finding globally optimal solutions is difficult and an analytical formulation of the solution is often infeasible. While *greedy search* techniques have been popularized over the last few years in the area of resource allocation in multiuser OFDMA scheduling [87], [89], their application to multi-cell resource allocation seems to have drawn attention only recently. In this case it operates by optimizing on a cell-by-cell basis, sequentially, just as individual users are optimized sequentially in the single-cell scenario. At each cell visited, the resource is optimized based on local channel conditions and newly updated interference conditions originating from the other cells [109], [110]. Such techniques may also be applied in an iterative manner by revisiting a sequence of cells several times until capacity convergence is reached.

Another important issue is the coordination of resource allocation over different coexisting air interfaces, considering the implementation of Common Radio Resource Management (CRRM) strategies. In fact, a plethora of wireless systems is now offered to users, and possible cooperation among them will lead to the so called *trunking gain* [111]. In the literature different approaches were proposed, ranging from loose coupling, according to which a common authentication mechanism among different air interfaces is allowed, to very tight coupling, according to which one of the air interfaces is seen actually as part of the other network [112], [113]. It is clear that a very strong interaction is required for joint allocation performed over different air interfaces. Although the problem has been under investigation for some years already, it is still far away from being solved, and before designing appropriate scheduling strategies across multiple air interfaces, it is still necessary to study and identify good Vertical Handover (VHO) techniques, which are a fundamental preliminary step, as it will be shown in Section 1.5.

At first sight, joint multi-cell resource allocation and scheduling do not lend themselves easily to **distributed** optimization because of the strong coupling between the locally allocated resources and the interference created elsewhere in the network. Hence the maximization of cell capacities taken individually will not in general result in the best overall network capacity. Nevertheless, over the last years, beside the classical cellular systems some other paradigms are emerging, such as ad hoc networks and cognitive radio. In such kind of network it is difficult to imagine some coordination, since it requires the definition of a control unit. However, such kinds of networks are composed of nodes which can appear and disappear also frequently. In this situation a distributed approach is mandatory.

In Fig. 1.2 and Fig. 1.3 the difference between a controlled and a distributed architecture in multi-cell scenario is reported. It can be noticed that in a controlled approach, there is a dedicated unit which collects information from each cell and uses them to take decisions about allocation in each cell under its control, thus also managing interference in the network, whereas in case of distributed approach each cell takes decisions autonomously about allocation, thus, some interference may occur, as emphasized in Fig. 1.3.

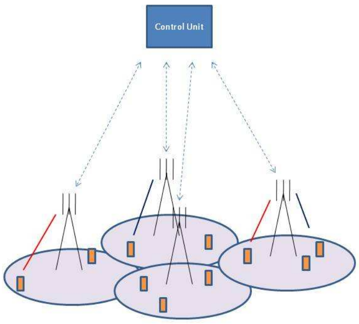

Figure 1.2: Controlled approach in multi-cell scenario.

Despite the fact that the ad hoc network concept is not new, the design of scheduling algorithms for such kind of networks has been emerging only recently, since traditionally Carrier Sensing Multiple Access (CSMA) based strategies were implemented, because ad hoc networks are characterized as peer-to-peer, and channel access should happen in a distributed way. This poses new challenges, such as the partial knowledge of the rest of the network at each node and, in extreme situations, the totally blind allocation process. The problem shows such a complexity that it is still difficult to find in the literature some works dealing with scheduling in ad hoc networks [47], [114], [115]. However, due to the always increasing demand of multimedia applications, it is hard that CSMA can cope with complex QoS management.

Among the very few works about scheduling over distributed systems an approach relies on the idea that interference behavior can be made more predictable by making the network larger or denser, and consequently the resource allocation problem in a given cell is made more dependent on the local channel conditions in that cell, thus facilitating distributed optimization [116]. Moreover, some interesting asymptotic

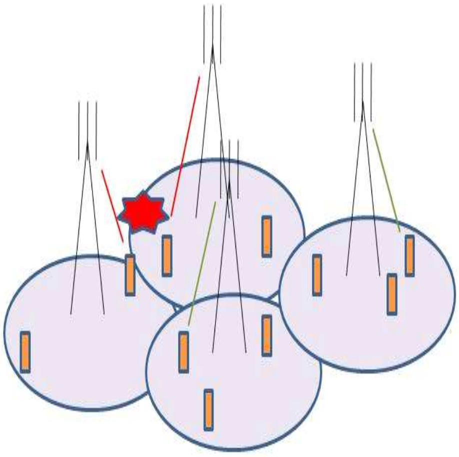

Figure 1.3: Distributed approach in multi-cell scenario.

results dealing with the case where the number of users per cell is sufficiently large can be mentioned. Indeed in this case, it can be shown that although the complexity of multi-cell scheduling and resource allocation seems to grow exponentially large, under the effect of scheduling maximizing sum capacity, intercell interference tends to vanish, making distributed resource allocation much simpler than in the small number of users case [61]. However, while cellular systems already show a wide literature about scheduling, the potential of scheduling over distributed networks is still largely unexplored, and for this reason the state of the art about scheduling over distributed network is still in a very preliminary phase.

1.4.1 Scheduling Techniques for Distributed Networks

Distributed approach in scheduling is a rather new topic, since typically in distributed environments random access is implemented. Some works exist in the literature where distributed scheduling is proposed, and they typically present game theoretic approach, due to distributed nature of the tool.

Game Theory

An interesting and recently explored path toward enforcing a distributed control of resources has been through the use of game theoretic concepts. Game theory, in its non-cooperative setting, pitches individual players in a battle, each seeking to maximize a utility function by selecting one of several available strategic actions. In the resource allocation framework, users can be terminals competing for access in a single cell, or interfering transmit-receive pairs of a multiple cell network or an ad hoc network. The actions may be resource allocation strategies, and the utility may be capacity related. Non-cooperative game models allow transmit-receive pairs to maximize their capacity under reasonable guesses of what competing pairs might be doing [100].

The game theoretic framework is very well suited to network scenarios where infrastructure is sparse or completely absent, as in peer-to-peer and ad hoc networks. As an alternative to the traditional game theory approach above, it was recently proposed to exploit so-called cooperative games, in which the player essentially build trust into one another, with the aim of improving their own rate, via some form of bargaining. In the recent literature, the application of cooperative games was limited to spectrum sharing and cognitive radio, and in the case of the cooperative beamforming [117], [118], [119]. It was also used earlier in the context of cooperative OFDMA resource allocation [120], [121].

Iterative Approaches

As an alternative to game theory techniques, previous papers such as [57] have also investigated iterative algorithms for distributed multi-cell resource allocation. In such approaches, APs individually, and iteratively, make a decision on their transmit power and user scheduling so as to optimize their contribution to the sum rate.

1.5 The Potentialities of Coexisting Systems: Heterogeneous Networks

Heterogeneous networks are designed to extend the coverage offered by the single wireless systems which compose it, increase spectral efficiency and provide service at higher quality and lower price realizing flexibility at the expense of an increased complexity. In the literature, different degrees of integration have been presented:

- *open coupling*, according to which different and separate access and transport networks are present,
- *loose coupling*, according to which a link between the Authentication Authorization and Accounting (AAA) unit and the Home Location Register (HLR) allows a common authentication mechanism,
- *tight coupling*, according to which a certain network, *e.g.*, a Wireless Local Area Network (WLAN), is connected to the core network of the cellular system which perceive it as part of itself.

As an example, 3G Partnership Project (3GPP) standardizes UMTS Terrestrial Radio Access Network (UTRAN) and GSM/EDGE Radio Access Network (GERAN) to operate in tight coupling mode, so that the core network supports information exchange between the RNCs of each Radio Access Network (RAN) involved, thus allowing CRRM. This is responsible for dynamic and intelligent cooperation among different RANs depending on static and dynamic measurements with the following objectives:

- coordination of the different sets of resources controlled by the RRM functionalities of each system,
- trunking gain, in order to reduce the block error probability in case of RT applications and to increase throughput while reducing delay for NRT applications, and to reduce block probability in handover procedure,
- QoS management.

These objectives can be achieved through two different architectures, which are also depicted in Fig. 1.4:

- integrated CRRM, according to which functionalities are implemented in each single cell/AP in a coordinated way. In this case no new entities should be introduced;
- centralized CRRM, according to which a centralized node takes decision in an optimal way.

Despite the fact CRRM has been under investigation for years, there are still very few works about scheduling over different RANs, as [122]. This happens because a very tight implementation of CRRM is required, and several issues should be addressed, such as traffic division over different systems and the relevant packet synchronization and jitter control.

The dynamics of handover between two coexisting wireless standards and the consequent exploitation of the offered diversity by the use of multi-standard terminals

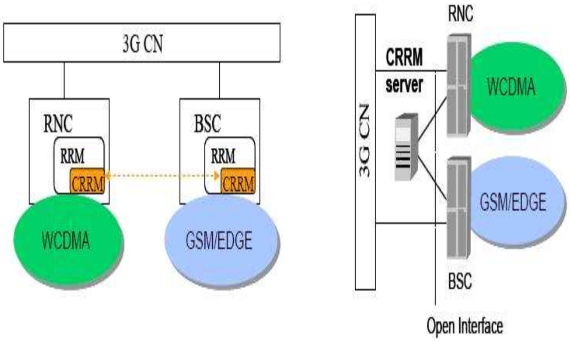

Figure 1.4: Integrated vs. centralized CRRM architecture.

should be investigated. The potential capacity benefits of mobile-initiated vertical handovers are substantial. However, it is important to choose the correct VHO criteria in order to achieve optimum load balancing and equilibrium states (global and social).

As a result of the massive deployment of coexisting wireless networks, mobile users often have several choices of collocated WLANs to connect to. This situation is exacerbated by the deployment of large scale mobile third-generation systems operated by major network operators, as well as other, smaller unregulated networks. In fact, mobile user chips already exist which support multiple standards and, additionally, there has been a significant amount of work in creating flexible radio devices capable of connecting to *any* existing standard [123]. It is therefore reasonable to expect that in the near future users will have the option to connect to different networks and to switch dynamically between them on a real-time basis, according to the offered throughput and/or price.

The dynamics of this process has several interesting aspects. Firstly, due to the lack of a central controlling authority mobile users become selfish and, even though users now have more choices to connect to, they still need to compete for the finite resources of nearby APs. Moreover, the repeated structure of the process makes users rely on past information available to them, in order to learn to adapt to the environment. To make things worse, since only local information about the past states of the system may be available, *e.g.*, the average service throughput per user, it is not clear how users may use this information in an effective manner. It is clear from the above that this process can be modelled in terms of a non-cooperative game. There have been two different directions of similar past work on this problem. To begin, there have been significantly extensive works on applications of game theory to wireless networks [100]. For example, uncoordinated random access channels have been analyzed by optimizing their transmission probabilities [123], or their power control [124]. Another application is in CDMA systems, as shown in [125], [126], [127]. More specifically, in the direction of connecting to multiple wireless nodes, [128] considered the possibility of connecting to several 802.11 APs using a single WLAN card.

Chapter 2

The Multi-Carrier Air Interface

3G and 4G transmission systems present the main characteristic of supporting many different classes of services to be provided to the user, with different requirements in terms of delivery delay and link quality (*i.e.*, BER). For this reason, the air interfaces which are being standardized within the new context, have to meet the different requirements adapting their characteristics to the QoS level needed by each application, which can consist of maximum BER, maximum delivery delay, minimum bit rate, et cetera. As a result, a very important role on the overall system performance of air interfaces will be played by the scheduling policies, whose aim is allowing suitable sharing of the radio resources between the different services.

Beside the plethora of applications available and to be managed, another challenge in today's wireless broadband access market is the ability to deploy and operate wireless systems able to guarantee good performance while delivering high speed data rate in many different topographic areas, where obstacles may affect the performance of the wireless systems due to Non-Line-Of-Sight (NLOS) conditions, which constitute a multipath-prone environment.

To face these new challenges, a new physical layer architecture based on a multi-carrier scheme, named Orthogonal Frequency Division Multiplex (OFDM), has been proposed in various works [129], [130], [131], [132], which has been actually chosen to be at the basis of broadband wireless standards like WiMAX [84] and LTE [85]. In this Chapter, an overview of the basic principles of multi-carrier transmissions will be provided. In particular, the functioning, the main characteristics, advantages and drawbacks, will be highlighted. The analysis performed in this Chapter basically applies to any MC-based system, having care of introducing the slight modifications related to the specific case under investigation from time to time, like in case of OFDMA or MC-CDMA systems. However, these will be specified in the proper Chapter when necessary.

2.1 The Principle of OFDM

OFDM is a multi-carrier modulation technique. Thanks to a parallel transmission scheme, it supports high speed serial data rates by splitting them up into a set of low-rate substreams, where each of these is modulated on a separate subcarrier, realizing Frequency Division Multiplexing (FDM). In Fig. 2.1, the simplified scheme of an OFDM transmitter emphasizing the multi-carrier dimension is depicted, where a_j represents the j-th high speed data sequence generated by a numerical source; $a_{j,n}$, with $n = 0, \cdots, N-1$, represents the portion of parallel data of sequence j converted from serial to parallel and conveyed on subcarrier n, where N is the total number of subcarriers available in the multi-carrier system; $d_{j,n}$ is the relevant data symbol resulting from the modulation; finally, the multiplication by the exponential is used to put data on the relevant subcarrier. It is worth noting that this sequence

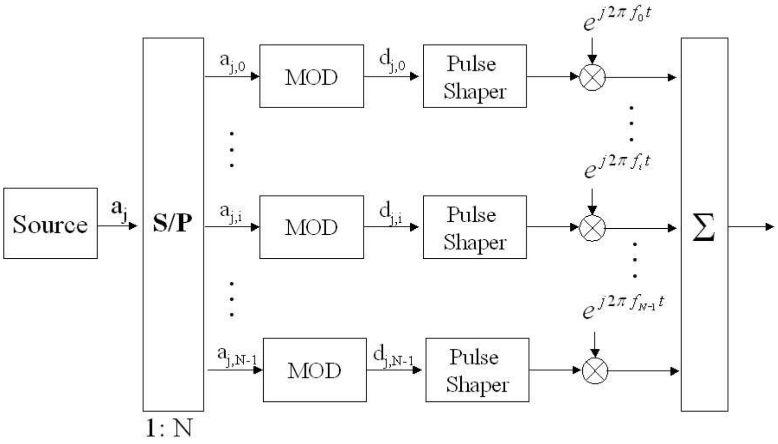

Figure 2.1: Logical scheme of an OFDM transmitter.

of operations is equal to performing an Inverse Discrete Fourier Transform (IDFT), which makes the implementation of such system easily feasible through the use of Digital Signal Processing (DSP) devices.

Among the most important characteristics of an OFDM signal, there is the fact that it counteracts Intercarrier Interference (ICI) and Intersymbol Interference (ISI). However, before illustrating how this is possible, some useful characteristics of wideband channels will be briefly recalled.

2.2 The Wireless Wideband Channel

In the presence of wireless mobile channels, the received signal is usually obtained as the summation of several "copies" of the original transmitted signal arriving through different paths [133]. In fact, differently from free space propagation, obstacles can obstruct the visibility between transmitter and receiver, as shown in Fig. 2.2. In particular three main physical phenomena can occur:

- reflection: when a wave encounters a boundary in its medium, and in general any surface with size much larger than the wavelength λ, it is reflected, *i.e.*, the wave is sent back in the direction of the direct wave;
- diffraction: when the electromagnetic wave passes through objects like, *i.e.*, trees, secondary waves are generated going in different directions departing from the obstacle;
- scattering: when the electromagnetic wave reaches an obstacle of size comparable with λ, several attenuated waves are generated travelling in various directions, realizing signal dispersion.

All these phenomena imply that the transmitted signal reaches the receiver via several paths with different delays, realizing several differently attenuated echoes, raising the phenomenon known as *multipath.* If the relative delays are large compared to the basic information unit transmitted (*i.e.*, the symbol or the bit duration), the signal will then experience significant distortion across the band. Moreover, transmission can be affected by the relative speed between transmitter and receiver. A wideband channel characterization should take into account these effects.

2.2.1 Frequency Selectivity

For sake of simplicity, let us consider an environment as shown in Fig. 2.3, where only a secondary path $s_d(t)$, attenuated and delayed with respect to the direct path $s(t)$, is generated due to multipath.

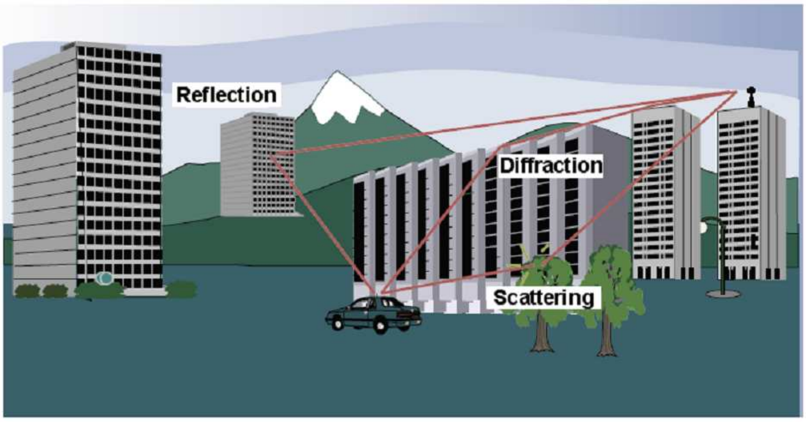

Figure 2.2: Reflection, diffraction and scattering in a multipath environment.

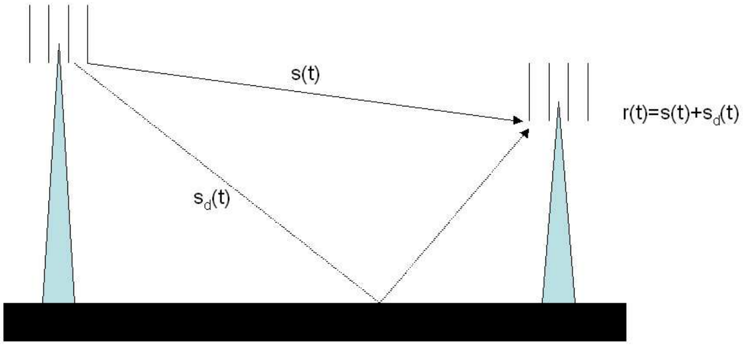

Figure 2.3: Simple multipath model composed of two rays.

If the original signal $s(t)$ is a generic wireless signal like:

$$s(t) = v(t)\cos(2\pi f_C t + \varphi_0), \tag{2.2.1}$$

where $v(t)$ is the envelope, f_C is the carrier frequency and φ_0 is the phase, its Fourier transform will be:

$$S(f) = \frac{1}{2}[e^{j\varphi_0}V(f - f_C) + e^{-j\varphi_0}V(f + f_C)]. \tag{2.2.2}$$

Since $s_d(t)$ is the secondary path, which is in general attenuated and delayed with respect to $s(t)$, it could be written in time domain as $s_d(t) = \gamma s(t - t_d)$. Thus, the Fourier transform of the received signal $r(t) = s(t) + s_d(t)$ will be:

$$R(f) = \frac{1}{2}[e^{j\varphi_0}V(f - f_C) + e^{-j\varphi_0}V(f + f_C)][1 + \gamma e^{-j2\pi f t_d}], \tag{2.2.3}$$

which means that the channel transfer function is:

$$H(f) = \frac{R(f)}{S(f)} = 1 + \gamma e^{-j2\pi f t_d}, \tag{2.2.4}$$

whose square module is:

$$|H(f)|^2 = 1 + \gamma^2 + 2\gamma\cos(2\pi f t_d). \tag{2.2.5}$$

At this point, it is worth introducing the concept of coherence bandwidth. The coherence bandwidth B_C is defined as the interval of frequencies over which the correlation of the channel frequency response is larger than a certain percentage $\Delta_{\%}$, and computed as:

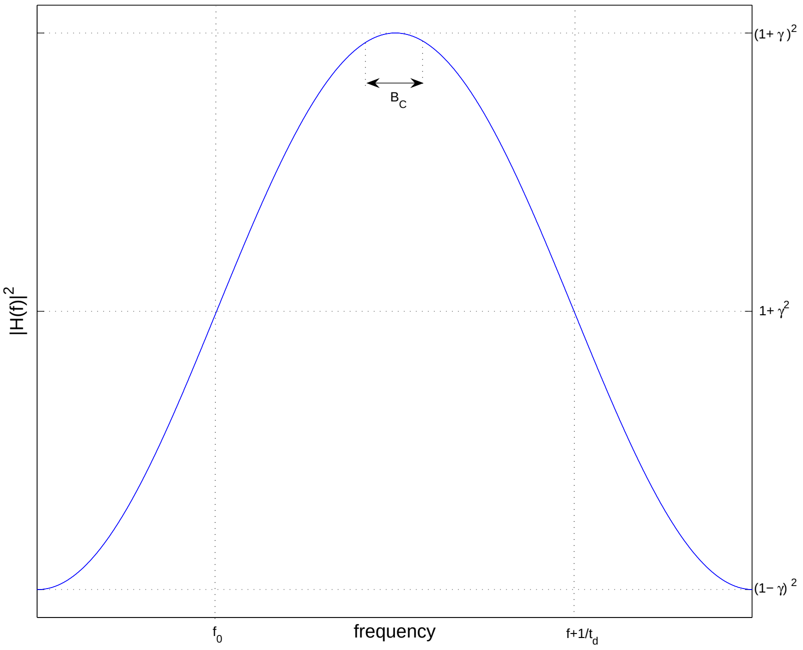

Figure 2.4: Transfer function square module of the two ray channel model.

$$\int_{-\infty}^{\infty} H(f)H(f+B_C)^* df \geqslant \Delta_{\%}. \tag{2.2.6}$$

From this simple considerations, it can be argued that frequency selectivity due to multipath is strongly related to the delay t_d and the attenuation γ among the various paths. However, in a realistic system, the number of paths is actually larger than two. Thus, the analysis should be extended by considering all paths with significant power. In this case, the coherence bandwidth will still be related to the delay among paths, and in particular to an aggregated metric named Root Mean Square (RMS) delay spread, defined as:

$$\tau_{RMS} = \sqrt{\frac{1}{P_T}\sum_{i=1}^{n} P_i t_i^2 - t_0^2}, \tag{2.2.7}$$

where P_T is the total power in the channel, computed as $P_T = \sum_{i=1}^{n} P_i$, where P_i is the power associated to the i-th path out of n, t_0 is the mean delay defined as $t_0 = \frac{1}{P_T}\sum_{i=1}^{n} P_i t_i$, t_i is the delay associated to path i. So, in presence of multipath fading, the coherence bandwidth will be inversely proportional to the RMS delay spread. In Table 2.1, some typical RMS delay spread values are reported depending on the propagation environment. The more the environment is scattered, the more the channel is frequency selective.

Table 2.1: RMS delay excess values depending on the propagation environment.

Environment	Approximate RMS delay spread in μs
Indoor cells	0.01-0.05
Mobile satellite	0.04-0.05
Open area	<0.2
Suburban macrocell	<1
Urban macrocell	1-3
Hilly area macrocell	3-10

Finally, the Probability Distribution Function (PDF) of a sum of statistically independent random processes, is identical to the convolution of all PDFs. However, the central limit theorem states that a sufficient number of independent random processes are approximatively Gaussian or normal PDF: according to its mean, the magnitude of a complex-valued Gaussian process is Ricean or Rayleigh distributed if, respectively, a line of sight exists or if no line of sight is available.

2.2.2 Time Variance

The effects of frequency selectivity are fading away the more narrowband a signal becomes. However, the Doppler effect plays a crucial role in this case. This is caused by the relative displacement between transmitter and receiver, and results in the receiving signal being shifted (in frequency domain) by the so called Doppler frequency $f_D = \frac{v}{c} f_C \cos\alpha$, which is in turn a random process, where v is the relative speed between transmitter and receiver, c is the speed of light, f_C is the carrier frequency and α is the angle of arrival of the path.

By considering the receiving signal as a superposition of several discrete frequencies of same amplitude, the PDF describes the amount of spectral lines in a frequency segment $\triangle f$. The power within this segment is obtained by adding the powers of the spectral lines included in the segment. In presence of Doppler effect, the spectral distribution of the power corresponds to the power spectral density, which is according to the so-called Jakes distribution [134].

The time variance causes the frequency response to dramatically decrease at certain time intervals, and the effects of time variance are increased the more narrowband a signal is, due to the longer symbol duration corresponding to a higher possibility of changing channel properties within one symbol interval.

2.3 Potential and Advantages of OFDM Systems

As previously investigated, though a narrowband signal is preferable to combat the effects of frequency selectivity, time variance affects especially symbols of long duration, leading to a small symbol duration to be desirable. For this reason, it is opportune to find a modulation scheme able to provide an optimal trade-off between the effect of time variance and frequency selectivity.

The reduction of the effects of a multipath (frequency-selective) channel achieved by multi-carrier systems can be illustrated in frequency domain: the bandwidth of the single subcarriers is small compared with the coherence bandwidth of the channel, *i.e.*, each subcarrier experiences flat fading. Thus, due to the narrowband transmission on single subcarriers, the equalization at the receiver is simple since it can be performed as for flat fading channels, *i.e.*, it is reduced to a simple complex multiplication. Contrarily, a single-carrier wideband transmission is distorted by the complete frequency-selective transfer function. However, the symbol period of the substreams is long compared to the delay spread of the time-dispersive radio channel.

Moreover, OFDM allows to obtain high spectral efficiency, since the spectra of the subcarriers overlap while avoiding mutual influence between each other (ICI). In fact, OFDM systems are able to cope with ISI and ICI distortions, by choosing a filter-function fulfilling the first Nyquist criterion in time domain, leading to an always ISI free system: working with rectangular impulse in time domain, an OFDM system is composed of infinite extended *sinc*-shaped subchannel spectra. The corresponding spectra are overlapped, but the maximum of each subcarrier (hence, of each *sinc* function) corresponds to the zero of all other subcarriers in the system, realizing orthogonality in frequency domain, as show in Fig. 2.5, hence the name Orthogonal FDM. Finally, to enable ISI resistance even for real multipath channels a so-called cyclic prefix is introduced.

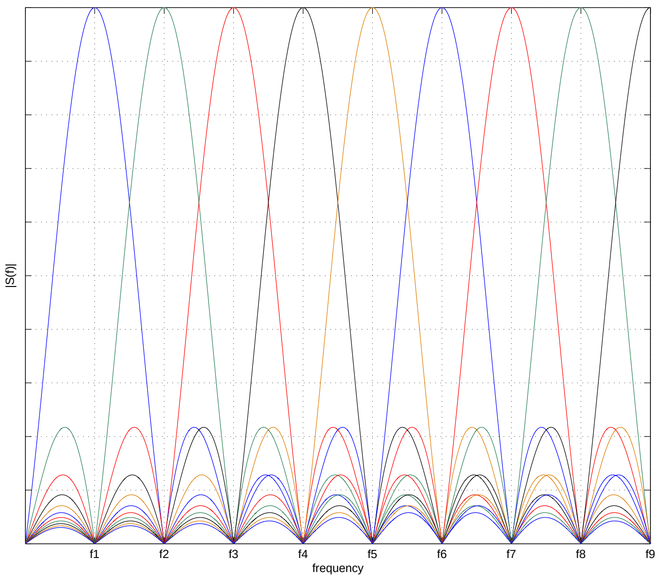

Figure 2.5: Spectrum of an OFDM signal.

Besides counteracting ICI and ISI, there are other important advantages in utilizing OFDM based systems. Adaptive modulation schemes can be used and suited independently on each subcarrier according to the specific Signal-to-Noise–Ratio (SNR) perceived, thus allowing a better spectral efficiency. Nevertheless, as already mentioned, the implementation of an OFDM system is easy to realize since it simply consists in an IDFT in transmission, as it can be noticed in Fig. 2.1, and dually in a Discrete Fourier Transform (DFT) in reception.

The advantages of this technology, combined with the ability of supporting high data rate transmissions, made multi-carrier based systems the ideal candidate for modern and future broadband wireless systems like WiMAX and LTE.

The most interesting aspect of OFDM systems related to this Thesis, is that they introduce a new degree of freedom in resource allocation. In fact, the multi-carrier aspect can be seen as a new dimension in multiple access: several users sharing the wireless channel, can be allocated on one or several of the subcarriers available in the system, and possibly in combination with other multiple access techniques like TDMA and CDMA. In this case, by emphasizing the multiple access aspect, it is more proper to talk about OFDMA. In such systems, usually a new unit in resource allocation is introduced, namely the Group Of Frequencies (GoF), which is a set of subcarriers, which constitutes the minimum allocation unit on the frequency axis. In case spreading sequences are associated (and superimposed) to GoFs, this new OFDMA system combined with CDMA is called MC-CDMA. A detailed description of such system will be provided in the next Chapter, since it will be the object of investigation of part of this Thesis.

Though OFDM-based systems show many potentialities and advantages, they obviously do not come for free. Thus, for sake of completeness, it is worth mentioning also the main drawbacks of such technology. As already mentioned, the longer the duration of a symbol, the stronger the effects of time variance on transmission. Moreover, the more subchannels are used, the more complex the implementation becomes. For that reason subdividing the available bandwidth in subcarriers, should be restricted to a certain extent, which should be suitably designed. Nevertheless, synchronization issues are raised by OFDM systems both in time and in frequency, in order to guarantee annulation of ISI and ICI. Besides this, the non-constant power envelop along subcarriers, asks for a careful use of linear amplifiers. Finally, in order to exploit at its best the potentiality of OFDM, efficient channel estimation techniques should be designed and implemented.

Chapter 3

The Cross-Layer Construction

Current and future cellular networks need to provide wireless connectivity to heterogeneous users, offering many different data traffic types with separate properties in terms of data burst interarrival time distribution, average bit rate, etc.: File Transfer Protocol (FTP), audio, video, web browsing, et cetera. For this reason, nowadays wireless multi-channel scheduling over complex air interfaces is considered as one of the main instruments for network optimization [64]. However, with air interfaces such as OFDMA and MC-CDMA, scheduling operations become more and more complex due to the numerous degrees of freedom, *e.g.*, subcarriers, time slots and, possibly, spreading sequences. As a matter of fact, cross-layer design of algorithms has been under investigation for long time [135]. However, a fully optimized scheduling in such wireless systems could require infeasible complexity. For this reason, though sub-optimal, a decomposition of the scheduling problem in simpler subfunctionalities, if properly performed, could lead to a significant complexity reduction, while keeping guaranteeing satisfactory performance.

Optimized transmission strategies for a mixture of different wireless multimedia services are investigated in the literature. Among them, channel-aware scheduling algorithms [81], joint radio link buffer management [136], and several other resource allocation strategies, could be mentioned. However, it is not yet clear how approaches perform with respect to each other, and whether they can be combined in a reasonable manner. Since most of them heavily rely on cross-layer design principles, it is impossible to compare them via simple theoretical analysis.

In this Chapter, an overview of the different cross-layer approaches present in the literature is provided, a formal separation of the scheduling function into two subfunctionalities is proposed. Then, a cross-layer architecture involving several layers of the traditional International Standard Organization/Open System Interconnection (ISO/OSI) protocol stack, namely, PHY, MAC, network, and application layers is introduced. This architecture has been implemented and tested through the development of a simulation environment performed with researchers of the Technical University of Munich and the University of Ferrara, in the context of a collaboration within Network of Excellence in Wireless Communications (NEWCOM). This software tool is used to investigate the effectiveness of newly proposed transmission strategies for mixed services.

3.1 Cross-Layer Approach

While requirements of different services, *i.e.*, video, background and sensor data, have to be fulfilled, the system capacity in terms of overall transmitted data rate has to be increased as much as possible. The strategy that best fits the latter requirement is the widely-used opportunistic scheduler, which takes into account fluctuations in the channel characteristics of each user, as described in the previous Chapter. However, while this purely channel-adaptive behavior maximizes the overall transmitted data rate, the drawback is that users with bad receiving conditions may be temporarily blocked, which is especially critical for delay-sensitive services. So, a cross-layer approach in scheduling could be beneficial in order to manage differentiated QoS.

As Srivastava has formalized in [32], the cross-layer concept can be implemented in many ways:

- creation of new interfaces: this is possible in three versions, namely “upward information flow”, “downward information flow” and “back-and-forth”. In the former version, a higher-layer protocol that requires some information from the lower layer(s) at runtime, results in the creation of a new interface from the lower layer(s) to the higher layer; in the second version the information flow is the other way round, and in the latter is bidirectional;
- merging of adjacent layers: two or more adjacent layers are designed together such that the service provided by the new superlayer is the union of the services provided by the constituent layers;
- design coupling without new interfaces: this implies a cross-layer design which involves coupling two or more layers at design time without creating any extra interface for information sharing at runtime;
- vertical calibration across layers: as the name suggests, this refers to adjusting parameters that span across layers. The motivation is that the performance seen at application level is a function of the parameters at all the layers below it. Hence, it is conceivable that joint tuning can help to achieve better performance than individual setting of parameters can achieve.

In the following, the case denoted in [32] as "back-and-forth" will be considered. However, before describing in detail the architecture object of investigation and its cross-layer interactions, it is necessary to introduce the formal separation of the scheduling function which is the basis of the following two Chapters.

3.2 Cross-Layer Scheduling: a Functional Split

For optimal distribution of resources among multiple users, the scheduling unit has in general to jointly consider all users in the decision process. This, however, requires the evaluation and comparison of a large number of possible allocations. Given that typical interscheduling intervals are of length 10 ms and less, this approach is practically infeasible. This is the motivation why in the following the principle of "opportunistic distribution" of resources and a functional split of the scheduling function, which in the literature are sometimes used as synonyms, like [38], [39], and in other case indicate separate tasks, like [35], [66], is introduced.

The scheduler is responsible for the selection of the users to be served and the set of resources over which users should be allocated. So, it is possible to split the whole function into two subfunctionalities, which separate the "temporal" dimension of the problem from the one strictly related to the transmit system. In this case, the "scheduler" could be defined as a completely air interface-unaware module, responsible for the selection of the user(s) to be served in the next time interval according to a specific policy. On the contrary, the "resource allocator" could be defined as a completely air interface-aware module, responsible for the selection of the set of RUs to be allocated to each of the scheduled users.

While this strategy is suboptimal, it nevertheless represents a good first approximation to fully joint distribution of resources. Nevertheless, it is worth noting that this structure is formalized in such a way to be applicable to any wireless system.

3.3 System Architecture and Cross-Layer Implementation

As already mentioned, current and future multi-carrier based systems should cope with different traffic types, each characterized by specific statistic properties, and time-varying frequency-selective channel behavior. In case a cross-layer approach is of interest, many different components belonging to different layers, *i.e.*, buffer entities, PHY, application layer et cetera, should be also considered. This makes any analytical performance evaluation of prohibitive complexity, leaving the simulation approach as the only possible. For this reason a complex $C++$ software tool, named CROESUS, CROss layEr-based SchedUling Simulator, able to simulate the characteristics and the functionalities of the most interesting layers for scheduling, has been developed. The aim of such software was to study a cellular system over which packet-based mixed realistic traffic sources are competing to access the wireless shared channel, as shown in Fig. 3.1.

As emphasized in Section 3.2, a formal separation of the whole scheduling function into two subfunctionalities, namely, “scheduling” and “resource allocation”, is considered. In Fig. 3.2 the architecture of the system, including the relevant functionalities involved in cross-layer operations, is reported: the application module generates data

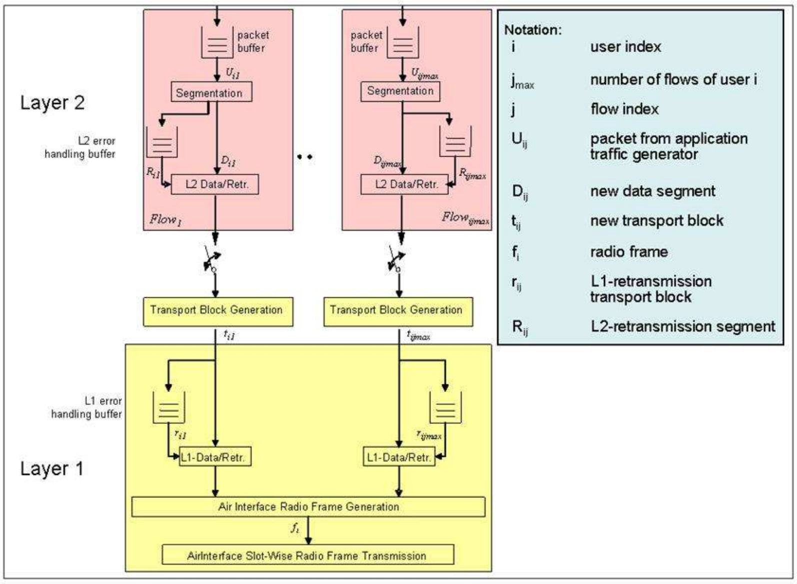

Figure 3.1: Scheme of the packet-based system implemented.

according to realistic traffic models and sends them to the buffer management module, which controls the packet to be flowed to lower layers and drops some of them upon request according to the policy implemented; then, the air interface sends channel information to the resource allocator which, consequently, sends proposals for allocation to the scheduler, where the scheduling metric is computed. The scheduler selects the users to be allowed to transmit, and notifies the buffer management entity about flows to be scheduled and the air interface about the relevant radio resources to be allocated; finally, data are sent to the air interface, which prepares the transport formats and transmits signals over the wireless shared channel.

Looking at the flow chart of the system behavior in Fig. 3.3, it could be noticed that an iterative process takes place between scheduler and resource allocator: at each scheduling time instant the resource allocator, in a completely air interface-aware

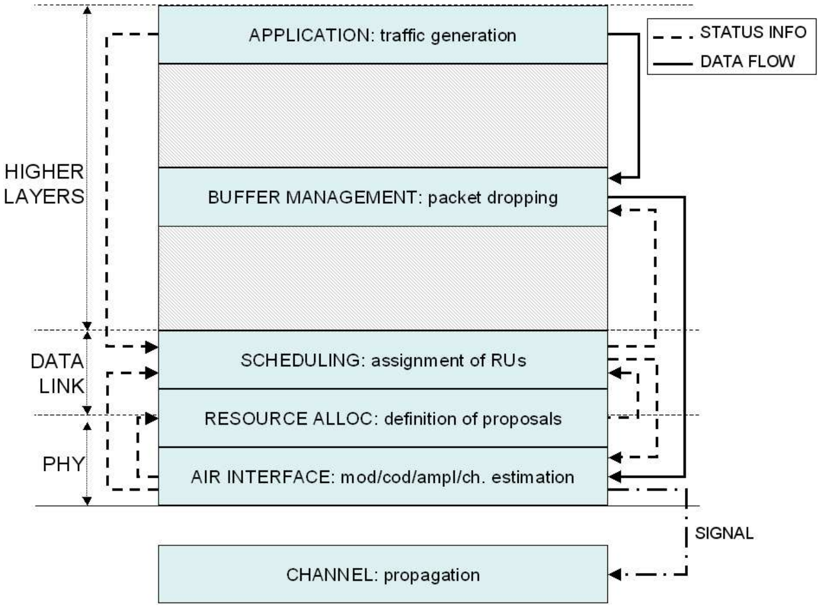

Figure 3.2: System architecture and cross-layer implementation.

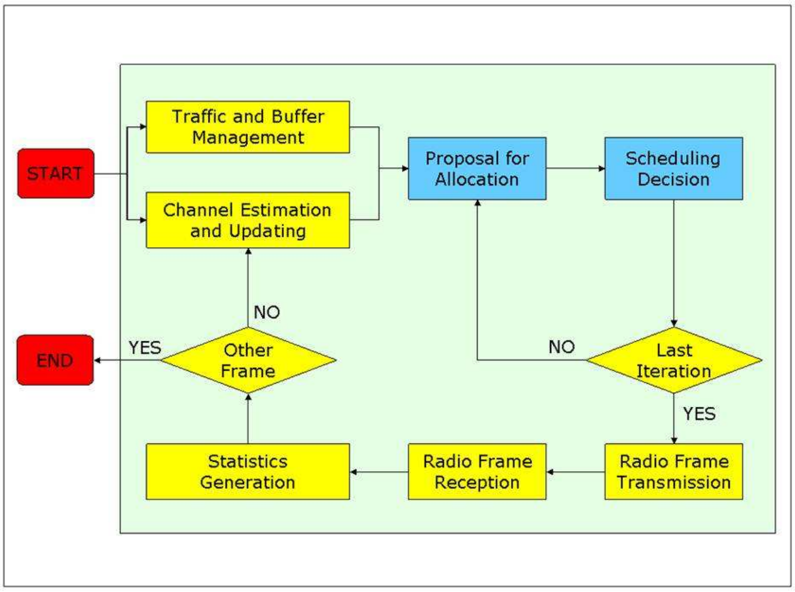

Figure 3.3: Flow chart of system behavior.

manner, formulates independent allocation proposals for each user with a non-empty radio link buffer, based on the currently available common resource budget in the system. The resulting set of proposals is then forwarded to the scheduler which selects the best proposal in the current set according to the desired scheduling policy. In addition to the information that can be deduced from a proposal, the scheduler might also take into account additional side information from other parts of the system in its decision. According to this, the resources required for the selected best proposal are removed from the budget, and the resource allocator determines new proposals for the other users based on the remaining resource budget, which are again forwarded to the scheduler for another round. This iterative process is repeated until either all users with data to be transmitted have been allocated, or the remaining resource budget is empty. In the following the main characteristics of the system under investigation will be reported and described in detail.

As a final remark, it is clear that the selection of the user to be scheduled should be jointly performed with the selection of the RUs allocated. However, the split of the whole scheduling functionality into two stages, allows an easier implementation: when selecting the user to be scheduled, the parameters required are at a higher level of abstraction with respect to the level of detail of physical layer, introducing a significant gain in terms of complexity. Despite the sub-optimality of the strategy, a good approximation to fully joint resource distribution is reached and, nevertheless, a cross-layer approach is implemented since a tight interaction of the scheduler with the application level and the physical layer is considered.

3.4 Scenario Overview

In the following two Chapters, results related to the cross-layer architecture presented will be reported. The two Chapters refer to different scenarios but they have some characteristics in common: in particular in Chapter 4 the case of a wireless cellular system where mixed traffic composed of video and NRT users compete for the shared channel, is considered; whereas in Chapter 5 a wireless ad hoc network composed of heterogeneous devices organized in a hierarchical structure, is investigated. However, both systems share the MC-CDMA air interface, the channel model, the set of buffer management strategies. For this reason, characteristics/models used in the next two Chapters will be presented in the current one. Thus, the resource allocation strategies and the benchmarks of the scheduling policies proposed in the next two Chapters are also reported.

3.4.1 MC-CDMA Transmission System

The transmission system used is MC-CDMA, as depicted in Fig. 3.4 for the transmit side: every symbol time a vector of P modulated symbols feed the inputs of the system. Each of these symbols is multiplied by a spreading sequence of length K, and the resulting K channel symbols are modulated in parallel over a group of K contiguous subcarriers, named GoF, of an OFDM transmitter, so that an IDFT is performed. The total number of available subcarriers is $N_C = K \times P$. It is worth noting that up to K different modulated symbols can be transmitted over the same GoF by using different orthogonal spreading sequences. A guard time interval is inserted at the end of each OFDM symbol before the final modulation at carrier frequency f_c.

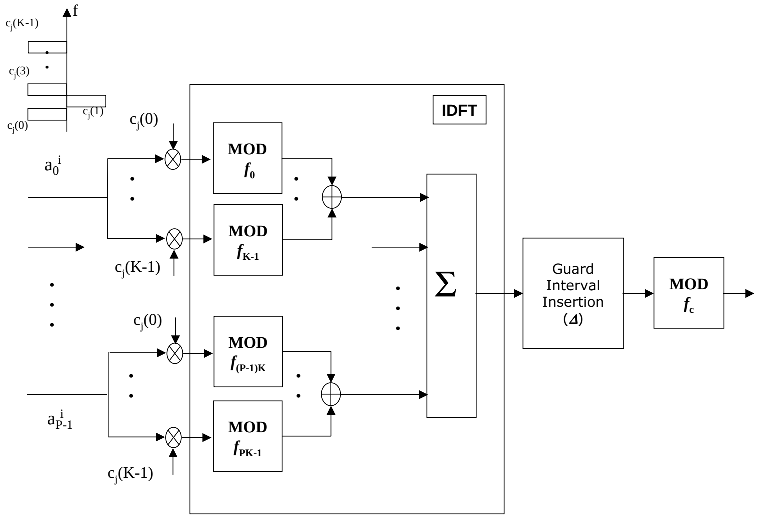

Figure 3.4: MC-CDMA system.

Data symbol transmission is organized in frames of fixed duration, called a Transmission Time Interval (TTI). Each frame is composed of a certain number of time slots. All mobile terminals in the cell are assumed to be synchronized at both frame and slot level. If the number of slots within the frame devoted to the uplink is N_{UL}, by using orthogonal spreading codes, the system offers a total of $N_{RU} = N_{UL} \times K \times P = N_{UL} \times N_C$ RUs in each frame for the uplink[1].

At the receiver side, a multiuser detector is added to separate the different data sequences transmitted over the same GoF with different spreading codes. For a single data sequence transmitted over one GoF, a perfectly synchronized receiver performs Maximal Ratio Combining (MRC) of the signals coming from the K subcarriers. In presence of multiple data sequences sharing the same GoF with asynchronous transmission due to multipath propagation, multiple access interference may arise

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[1] An RU is defined here as a particular set composed of one GoF - one slot - one code.

[137]. Since a multiuser detector is able to minimize the interference coming from known mobile terminals in the same cell, the intracell interference is assumed to be negligible, whereas intercell interference coming from adjacent cells, since it can not be counteracted, should be taken into account.

To perform evaluations, $N_C = 64$ subcarriers, with bandwidth Δf=24.4 kHz, are considered to be organized in 4 GoFs, so the spreading sequence length K is 16; the TTI lasts 10 ms and is composed of 5 slots all devoted to the uplink. The roll-off factor α is equal to $\frac{1}{4}$ and the noise system temperature is 2900 K. The maximum number of RUs per user is $N_{RUmax,u} = 96$. The maximum power per user P_M is 2 Watts and the cell radius R is 100 m.

3.4.2 Channel Model

A time-variant frequency-selective multipath fading channel is assumed, according to the "Pedestrian B" channel model proposed in [138] for 3G mobile systems. In particular, each user i is affected by pathloss modelled as in [139]:

$$L_i(dB) = k_0 + k_1 \ln(d_i), \tag{3.4.1}$$

where $k_0 = 40$ dB, $k_1 = 15.2$, d_i is the distance between the randomly and uniformly distributed user i and the BS. Moreover, multipath fading is superimposed: it is a channel impulse response composed of six complex Gaussian distributed paths with fixed power delay profile. For each path the classical Doppler spectrum, *i.e.*, Jakes [134], characterized by the normalized autocorrelation function $R(\tau) = J_0(2\pi f_d \tau)$ is considered, where $J_0(\cdot)$ is the Bessel function of the first kind of order zero, while f_d is the maximum Doppler shift, assumed to be $f_d = 6.66$ Hz for a pedestrian environment, and the maximum delay spread is $\tau_s = 3.7$ μs. Moreover, log-normal shadowing with standard deviation $\sigma = 6$ dB is added.

While the pathloss is kept constant but different for each user over the evaluation time of the experimental setup, the shadowing sample is updated every second according to an exponential correlation model with correlation distance $D_{corr} = 20$ m. Finally, block fading, in the sense that the multipath fading a user experiences is constant over one frame, is considered.

3.4.3 Traffic Models

In the scenarios to be investigated in the next two Chapters, different mix of traffic will be considered. In the following all traffic models taken into account in the analysis will be presented.

Video

$N_{U,v} < N_U$ mobile terminals in the cell want to transmit a pre-encoded Variable Bit-Rate (VBR) video stream, *e.g.*, some video sequences previously shot with a built-in camera device. In particular this is a H.264/Advanced Video Coding (AVC)–coded Quarter Common Intermediate Format (QCIF) sequence of length $N_v = 2698$ frames as in [136], with $QP = 28$, 30 fps, and no rate control. The duration is $T_v = 90$ s and average bit-rate $R_v = 185.2$ kbit/s to a peer entity in the network. Each video packet contains exactly one frame and has a deadline which depends on the nominal video decoding timeline according to which the packets are sent, and a fixed *initial delay* $\delta_{\text{init}} = 2$ s due to the dejitter buffer at the peer entity. Video packets which arrive beyond their deadline are assumed to be no more useful to the decoder and are discarded, performing the so-called *late-loss*. In addition, the temporal dependencies among video frames, which result from the use of hybrid video codecs and can be represented via directed acyclic graphs [140], are considered in the evaluation process: a standard Group of Pictures (GoP) structure of IBBPBBP... is assumed to account for the dependencies, with an I–frame distance of 1 s. The overall Peak-Signal-to-Noise–Ratio (Y-PSNR) is $Q_v = 36.98$ dB. Any missing video frame is concealed by the timely–nearest reconstructed frame. The resulting service quality for video users could be measured by the Y-PSNR of individual frames in the stream of a user.

Unconstrained Delay Data

A simplified Unconstrained Delay Data (UDD) traffic model is used in some simulations, according to which data at same average bit-rate $R_b = 178.5$ kbit/s are sent to the peer entity. UDD packets are of fixed length 1500 bytes and their generation time instants are uniformly distributed over the simulation duration for each user. Since these packets have no strict deadline, the service requirement for them is specified in terms of target average throughput and delay.

File Transfer Protocol

FTP data are considered as specified in [139]: packet calls are generated according to a Poisson process with average rate 1.1, the number of packets per packet call has a Geometric distribution with mean value 6. The distribution of the packet interarrival time is Geometric with mean value 2, whereas the packet size is Pareto distributed with shape parameter 1.1 and scale parameter with minimum value ranging from 64 to 1048576 bytes and maximum value from 256 to 5242880 bytes depending on packets, which could be small, medium or large with probability $\frac{1}{3}$.

Sensor Data

In the ad hoc network scenario, also sensor data are considered. In particular the devices considered are according to IEEE802.15.4 [141]. However, since data structure is strictly related to the MAC protocol implemented, all application details will be provided directly in Chapter 5.

3.4.4 Buffer Management Strategies

Scheduling strategy is used combined with the radio link buffer management strategies proposed in [136]. These strategies are beneficial if the channel quality of some delay-constrained user is currently poor and the radio link buffer cannot be emptied fast enough: in this case, application-aware dropping of packets is already done at the transmitter to reduce the excess load and convert late-loss at the receiver, due to expired packet deadlines, into controlled packet removals.

In detail, the following buffer management strategies, also described in [136], have been applied.

Infinite Buffer Size

This simple strategy is used for NRT traffic with no explicit deadlines: each radio link buffer has infinite buffer size $N_{\mathrm{RL}} = \infty$. Hence, no packets are dropped at the transmitter, resulting in variable delay at the receiver.

Drop Dependency Based

For video users, only a finite number $N_{\mathrm{RL}} = 60$ of packets is stored in each radio link buffer. In case it reaches its maximum, dropping of packets is performed as follows: basic side-information on the structure of the incoming video stream is available to the buffer management, *e.g.*, the GoP structure and its relation to frame/packet dependencies. The Drop Dependency Based (DDB) strategy operates on the Head-Of-Line (HOL) group of packets with interdependencies. While all packets with no dependants can be deleted starting from the beginning of the HOL group, any other packets should be first removed from the end of the HOL group to avoid broken dependencies. Since the structure of the video stream is usually fixed during one session, the buffer management only has to determine this information once during the setup procedure.

Simple Finite Buffer Size

In case data under investigation are not characterized by hierarchical structure, which means that no different priority in packets can be identified, but deadline is defined, Simple Finite Buffer size (SFB) is assumed, according to which buffers have fixed size N_{LB_s} in terms of packets that can be stored.

3.5 Resource Allocation Strategies for MC-CDMA

The MC-CDMA resource allocator formulates proposals which contain the following information: the amount of bits to be transmitted, *i.e.*, the transport block size, the number of RUs required, the modulation and channel coding scheme to be used and the transmit power needed. The allocation parameters can be selected in many ways, ranging from a very adaptive to a completely blind one. In the following subsections, an adaptive implementation of the resource allocator module is proposed with two much simpler strategies used as benchmarks.

3.5.1 Adaptive Resource Allocation

The resource allocation module acts as follows: a user i can occupy up to $N_{RU,i} = N_{RUmax,u}$ RUs per proposal. RU selection involves several operations. First of all, for each GoF j with at least one slot and spreading code available in the resource budget, an estimate of the "*normalized SINR*[2]" at current frame t, $\widehat{SINR}_{i,j}$, is evaluated[3] as follows:

$$\widehat{SINR}_{i,j} = \frac{\hat{ch}_{i,j}}{P_{noise} + (1 - \frac{\alpha}{4}) \cdot \hat{P}_{int,i,j}\frac{2}{K}}, \tag{3.5.1}$$

where the numerator $\hat{ch}_{i,j}$ is the estimated channel state of user i on GoF j, evaluated by assuming perfect knowledge of the channel gain at frame $t - 1$ as:

$$\hat{ch}_{i,j} = \frac{\hat{\gamma}_{i,j}}{PL_i \cdot sh_i}, \tag{3.5.2}$$

where PL_i and sh_i are, respectively, the pathloss and shadowing affecting user i, whereas $\hat{\gamma}_{i,j}$ is the average multipath channel gain actually perceived by user i on GoF j at frame $t - 1$, obtained as:

$$\hat{\gamma}_{i,j} = \frac{1}{K} \sum_{n=j \cdot K}^{(j+1) \cdot K - 1} \hat{\gamma}_{i,n}, \tag{3.5.3}$$

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[2] This is evaluated by using a unitary transmit power in Watts per RU.

[3] The time index is removed to reduce the amount of indices to be used.

where $\hat{\gamma}_{i,n}$ denotes the multipath channel gain of the n-th subcarrier belonging to GoF j, which is constant over frame $t-1$, since block fading is assumed.

About the denominator in Eq. 3.5.1, P_{noise} is the noise contribution affecting user i and computed as:

$$P_{noise} = (1+\eta_g)K_B \cdot T_{sys}/T \tag{3.5.4}$$

where η_g accounts for the bandwidth loss due to the guard interval with cyclic prefix insertion, K_B is the Boltzmann constant, T_{sys} is the system noise temperature and T is the modulation symbol interval for each RU. Then, in Eq. 3.5.1 α is the roll-off factor of the raised cosine filter assumed at the receiver, K is the spreading sequence length and $\hat{P}_{int,i,j}$ is the estimated interferer power affecting user i on GoF j, computed as the interference power actually perceived at frame $t-1$.

The allocation algorithm runs in an iterative way to allocate the RUs of a given GoF J over all the available time-slots. Provided that the normalized SINR estimate $\widehat{SINR}_{i,J}$ is known, at each round h, with $h = 1, ..., H \leq N_{RUmax,u}$, a fraction P_M/h of power is assigned to the user and the estimated (not normalized) SINR $\widehat{SNIR}_{i,J}^{(h)}$ is computed, after assigning h RUs, as follows:

$$\widehat{SINR}_{i,J}^{(h)} = \frac{P_M}{h} \cdot \widehat{SINR}_{i,J}, \tag{3.5.5}$$

where P_M is the maximum power per user. At each round the modulation and coding format is chosen according to $\widehat{SINR}_{i,J}^{(h)}$ and the particular allocation strategy implemented; so, the supported rate $\hat{r}_{i,J}^{(h)}$ in bits per modulation symbol is determined. The number of bits, $\hat{b}_{i,J}^{(h)}$, conveyed by the set of RUs assigned to user i on GoF J at round h, is evaluated as:

$$\hat{b}^{(h)}_{i,J} = h\hat{r}^{(h)}_{i,J}T_{slot}, \tag{3.5.6}$$

where T_{slot} is the duration of a slot interval. Note that time slots and spreading codes are randomly chosen among those available, since this choice does not depend on the normalized SINR[4].

The process stops at round H when the maximum number $N_{RUmax,u}$ of RUs per user has been reached, or all available data in the radio link buffer of the user have been considered in the proposal, or the available resource budget has been used. At each step the number of assigned RUs increases, while the available power, and, consequently, the supported rate in case of link adaptation, decreases. Therefore, the final number of RUs proposed for user i on GoF J will be the integer $h = \hat{h}$ which maximizes $\hat{b}^{(h)}_{i,J}$.

This Adaptive Resource Allocation (ARA) strategy uses a fully optimized approach where all allocation parameters are jointly considered to meet the best possible allocation. Therefore, the strategy identifies for each user the best GoF also denoted as "*best group*" and proposes its allocation. Moreover, modulation and coding scheme is dynamically determined according to the channel state, which means that a link adaptation mechanism is implemented. The resulting rate $r^{(k)}_{i,J}$ is defined according to a set of thresholds suitably chosen in order to guarantee a block error probability below specified values.

For the ARA strategy, the modulation and coding schemes are respectively the Quadrature Phase Shift Keying (QPSK) format and a Bose-Chaudhuri-Hoequenghem (BCH) channel coding with coding rate equal to 1, 0.9, 0.8, 0.5, 0.1.

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[4] Different spreading codes are used in the same slot by the same user in order to prevent loss of orthogonality.

This strategy is adaptive to the channel state.

3.5.2 Benchmarks

As benchmarks, two much simpler strategies are considered, as follows:

Simple Resource Allocation

The second scheme considered is Simple Resource Allocation (SRA), which selects the best GoF as in ARA but no link adaptation is implemented in the system, *i.e.*, the modulation and coding format and, thus, the rate $\hat{r}_{i,J}^{(h)}$, are fixed. In this case only a coding rate equal to 0.8 is taken into account.

The strategy is not completely channel-adaptive.

Random Resource Allocation

The last allocation strategy considered is Random Resource Allocation (RRA), which selects the GoF randomly. This means that the normalized SINR is neither used to choose the best GoF, nor used to perform link adaptation. Also in this case only a coding rate equal to 0.8 is taken into account.

This strategy is not channel-adaptive.

3.6 Scheduling Benchmarks

3.6.1 Opportunistic Scheduler

The simplest idea for handling wireless shared channels – in contrast to fixed network – is the exploitation of the channel state perceived by each user through the so called Opportunistic Scheduling [142], [143]. Obviously, if the flow of the user with the best receiving conditions, *e.g.*, the highest SINR and, thus, the largest number of bits conveyed by the assigned RUs, is selected at any time instant, the overall system throughput is maximized. This scheduler is therefore referred to as Maximum Throughput (MaxTP). True maximization of throughput will obviously occur when MaxTP is combined to ARA. Nevertheless, it is therefore worth noting that, when MaxTP and ARA are jointly implemented, the functional split into scheduling and resource allocation does not introduce any loss. MaxTP with ARA will then be considered as a particular benchmark, allowing comparison of the algorithm based on the functional split, with a well known scheme jointly handling the two functionalities.

However, as users with bad receiving conditions are blocked, some unfairness is experienced in the system. Finally, as application side information is not used, application requirements may not be met by some users.

3.6.2 Wireless Fair Service Scheduler

Since throughput optimization might also lead to service starvation for users affected by bad channel quality, some mechanism should be introduced to preserve fairness among users. In the literature, a well known algorithm with this objective is WFS [73], [144], whose goal is to reach long term fairness among users. This balance is pursued through a compensation model governed by two counters per user, named *leading* counter and *lagging* counter, measuring the amount of credits and debts the users collected with respect to a reference error-free system. Obviously this strategy does not guarantee throughput maximization.

In practice, the algorithm tries to allocate first lagging users with good channel quality. In case this condition does not occur, then the algorithm selects leading users with good channel quality. The long term fairness is guaranteed by the counters, which are updated at each schedule, basically by decreasing the lagging counter in case scheduled user is lagging, or by increasing the leading counter of the scheduled leading user and, at the same time, by increasing also the lagging of non-scheduled lagging users.

3.6.3 Earliest Deadline First Scheduler

This is a widely known strategy, which simply compares proposals according to the deadline of the HOL packet in each data buffer [23]. The proposal chosen for allocation is the one with closest deadline, *i.e.*, the one nearest to the expiration time. This strategy is very simple and does not take into account any channel state information. Moreover, it can be implemented only in case of applications where deadline is defined. Thus, this strategy is implemented only for video traffic.

3.7 Performance Figures

In this Section, the metrics used to evaluate the performance of different scheduling and resource allocation algorithms are presented.

3.7.1 Outage Rate

This figure computes the fraction of time a video user perceives unsatisfactory service quality, *i.e.*, how many times video service requirements are not met. In particular, outage rate is computed as the number of frames with Y-PSNR smaller than 31 dB, which can be considered as satisfactory [145], divided by the total number of frames composing the video stream. On average, this should not happen more than 10% of the time, otherwise the user will consider the video service as not satisfactory.

3.7.2 Transport Block Error Rate

This is a link level metric, thus, usable for both video and NRT flows, and is computed for each user as the number of transport blocks not correctly received divided by the total number of transport blocks transmitted by the user.

3.7.3 Packet Loss Rate

This is a link level metric used for IEEE802.15.4 traffic, and is computed for each node as the number of packets lost due to any reason, *i.e.*, channel conditions and CSMA/CA, divided by the total number of packets transmitted by the node.

3.7.4 Fairness Index

This metric is introduced to evaluate the fairness level provided by an algorithm. To this aim, the widely known Jain's index [146], computed over a set $X = \{x_1, ..., x_N\}$ of N realizations of a particular metric x, is used:

$$J(X) = \frac{1}{N} \frac{[\sum_{n=1}^{N} x_n]^2}{\sum_{n=1}^{N} {x_n}^2}. \tag{3.7.1}$$

Obviously, given the metric set X, the more $J(X)$ approaches 1, the more the system is fair from the viewpoint of the performance metric considered. The Jain's index will be computed for the video users on the basis of both the Y-PSNR and the number of transmitted transport blocks. In fact, this way it is possible to check that fairness is guaranteed not only at application level, but also at link level in terms of transmission chances given to each user.

Chapter 4

Cross-Layer Scheduling in a Cellular MC-CDMA System

In this Chapter, a radio access network using a multi-carrier air interface is considered in a multi-cell multi-user context, where a new cross-layer scheduling algorithm which manages channel, physical layer and application related information is considered. The cross-layer scheduling strategy under investigation was first proposed in [81] for the uplink of Wideband-Code Division Multiple Access (W-CDMA) and has been then modified for a MC-CDMA system. The advanced scheduling algorithm proposed in this Chapter tries to find a good trade-off between maximizing throughput and meeting the individual deadlines of the data packets in the radio link buffers. Finally, a revised version, with some clever simplifications which however do not affect system performance, is proposed.

Scheduling is combined with the radio link buffer management strategies proposed in [136] and described in Section 3.4.4. The role of scheduling and resource allocation functionalities as defined in Section 3.2 are discussed. Nevertheless, the results reported, follow the evolution brought to the system design and modelling: firstly, a simplified scenario composed of a single cell with realistic video and a simple unrealistic NRT traffic model is considered; then, a more complex and complete scenario with intercell interference and realistic FTP traffic is analyzed. Performance of cross-layer scheduling are compared to well-known channel-aware or -unaware techniques, and its optimization is discussed. Results show that a channel- and application-aware algorithm, where fluctuations in the channel conditions of different users are exploited via statistical multiplexing, and application-specific requirements are also considered, can provide a larger number of satisfied video users.

4.1 Scenario

A cellular uplink scenario in an urban outdoor environment is considered with randomly distributed pedestrian users, where up to N_U mobile terminals can be active within the cell. Scheduling and resource allocation operations are centralized at the base station. Each mobile user has an active uplink control channel used to inform the base station about the current status of the buffer of each active data flow. Furthermore, the current channel status of each user is monitored. The problem to be addressed in such scenario is how to schedule users and assign radio resources with a cross-layer approach able to exploit information coming from the physical layer and the application level, jointly performed with buffer management, in order to guarantee better system performance. More details on the scenario will be provided according to the particular simulation results under consideration from time to time.

4.2 A Cross-Layer Channel and Application Aware Scheduler

An advanced scheduling algorithm for MC-CDMA systems is investigated, which tries to find a good trade-off between maximizing throughput and meeting the individual deadlines of the data packets in the radio link buffers, in the case of a single-cell uplink scenario. This strategy was first proposed in [81] for the uplink of W-CDMA and here has been modified, extended, and integrated into a resource allocator for a MC-CDMA system. In order to have a real cross-layer implementation according to the "back-and-forth" approach presented in Section 3.1, the scheduling function is combined with the radio link buffer management strategies proposed in [136] and described in Section 3.4.4, which allow to drop possibly outdated packets of delay-constrained users in an optimal way to reduce temporary excess load at the air interface, and with the opportunistic resource allocation strategy ARA presented in Section 3.5.1.

The simplest idea for wireless shared channels is the exploitation of the channel state of individual users. Obviously, if the flow of the user with the best receiving conditions, *e.g.*, highest SNR, is selected at any time instant, the overall system throughput is maximized. This scheduler is therefore referred to as Opportunistic Scheduler or MaxTP scheduler, and may be the most appropriate if throughput is the measure of interest. However, as users with bad receiving conditions are blocked, some fairness is experienced in the system.

In the following a Channel- and Application-Aware (CAA) scheduler is proposed, which does not base its decision solely on the current channel state, but on a dynamic priority metric for each user that combines the following parameters: the Time-to-Deadline (TD) T_D, the Type-of-Service (TS), and the Channel State (CS).

For delay-critical services, the TD value can be calculated in terms of number of TTIs as the difference between the deadline of the HOL packet in the radio link buffer and the current system time, whereas for services where no explicit deadline is set, the simplified assumption of a sufficiently large value of TD such that it can be assumed to be infinite, is made.

The TS value is used to differentiate the main priority level of the two services, *i.e.*, RT or NRT. Packets belonging to the same service are not differentiated further.

The CS value is computed for each user by the scheduler, based on the average channel gain γ of the relevant proposal sent by the resource allocator to the scheduler according to the procedure shown in Section 3.3. This is computed for each user i as the summation of $\hat{\gamma}_{i,j}$ defined in Eq. 3.5.3 over the number of RUs in the proposal under evaluation, divided by the total number of RUs in the proposal. Moreover, an additional parameter is the differential channel gain γ_d, defined as the difference in dB between the best channel gain achieved at the previous TTI and the estimated best channel gain in the current TTI. Having fixed two suitably chosen thresholds S_1 and S_2, the channel state can be classified according to γ[1] and γ_d into four cases:

a) γ is above S_1;

b) γ is between S_2 and S_1 and the γ_d is positive;

c) γ is between S_2 and S_1 and the γ_d is negative;

d) γ is below S_2.

---

[1] The user index is omitted in order to simplify notations.

The first case can be seen as a situation where fast transmission of the data block can be suggested; the opposite is true for case d). In the cases b) and c) it is useful to transmit packets only when the queue is long and they are approaching the deadline.

Finally, the priority metric $F(T_D)$ proposed is defined in the following way:

$$F(T_D) = \begin{cases} W + \max(0, A - (T_D - C) \cdot B), & T_D > C, \\ \infty, & T_D \leq C. \end{cases} \tag{4.2.1}$$

W, A, and B are coefficients depending on TS and CS. The delay coefficient C is equal to 0 if TS is NRT, whereas in case of RT services has to be suitably chosen: an interval of C TTIs should be granted to allow the scheduler to serve packets approaching the deadline when the traffic source has filled the buffer at peak rate. In fact, if C is set to be larger than 0, this is the same as artificially "shortening" TD. In this way it is likely that a single long packet or a sequence of packets at peak rate conditions will still be served.

To sum up, at each round the scheduling algorithm performs the following steps:

- for each proposal the priority metric $F(T_D)$ is evaluated according to the respective TD, TS, and CS. Then proposals are ranked in decreasing order of $F(T_D)$;
- the proposal with the largest value of $F(T_D)$ is scheduled. If the value of $F(T_D)$ is non-positive, no proposal is scheduled.

4.2.1 Numerical Results: the Single-Cell Case

To perform evaluation, an MC-CDMA air interface is considered according to the parameters set in Section 3.4.1. The channel is according to the models and parameters

Table 4.1: Values of coefficients W, A, B.

	TS=RT			TS=NRT		
CS	W	A	B	W	A	B
a)	1	200	1	5	0	1
b)	0	210	2.1	1	0	1
c)	0	200	2	1	0	1
d)	0	0	1	0	0	1

presented in Section 3.4.2. $N_U = 10$ pedestrian users are randomly deployed in the circular cell, and $N_{U,v} = 6$ users transmit H.264 compliant video traffic according to the parameters reported in Section 3.4.3, whereas the remaining $N_{U,b} = N_U - N_{U,v}$ mobile terminals in the cell transmit the simplified UDD traffic model described in Section 3.4.3. The scheduling strategy is combined with the buffer management strategies reported in Section 3.4.4, where DDB is associated to video traffic and Infinite Buffer Size (IBS) to UDD traffic, and to the ARA strategy introduced in Section 3.5.1. Finally, the scheduling parameters W, A, B used in this Chapter are given in Table 4.1. Parameter C is fixed to 0 for UDD users and will be optimized for video users. In the following, if not differently specified, performance are averaged over the whole simulation and all users transmitting the application under investigation.

Parameter Optimization

The first problem to be faced regarding the scheduling policy proposed, is to set proper values of the parameters involved.

Fig. 4.1 shows the CAA scheduler sensitivity to the channel state parameter S_1 for fixed $S_2 = 0.3$, and $C = 20$ for video and 0 for UDD users. For each video user the average Y-PSNR for three different S_1 settings in the CAA scheduler are evaluated and compared to the average Y-PSNR obtained with a MaxTP scheduler.

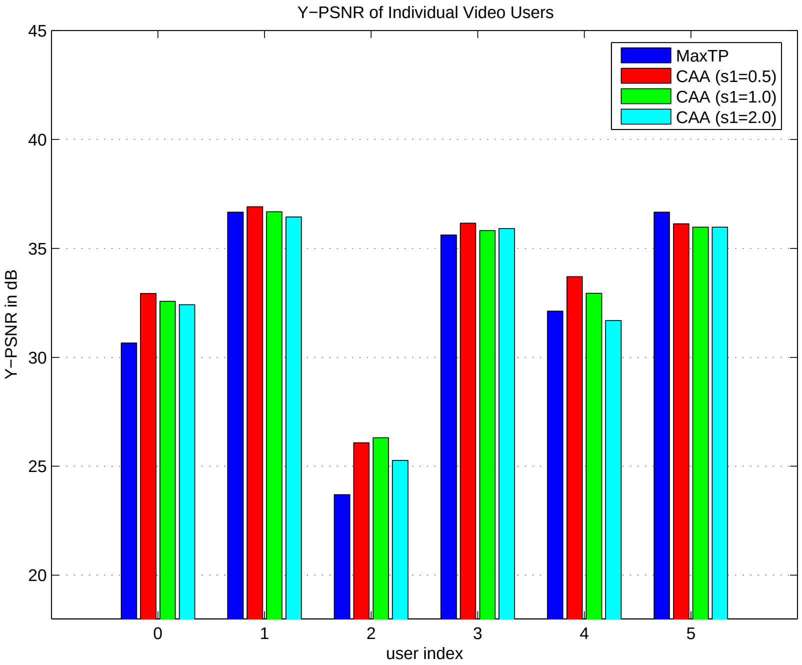

Figure 4.1: Y-PSNR for CAA and MaxTP depending on scheduling parameters.

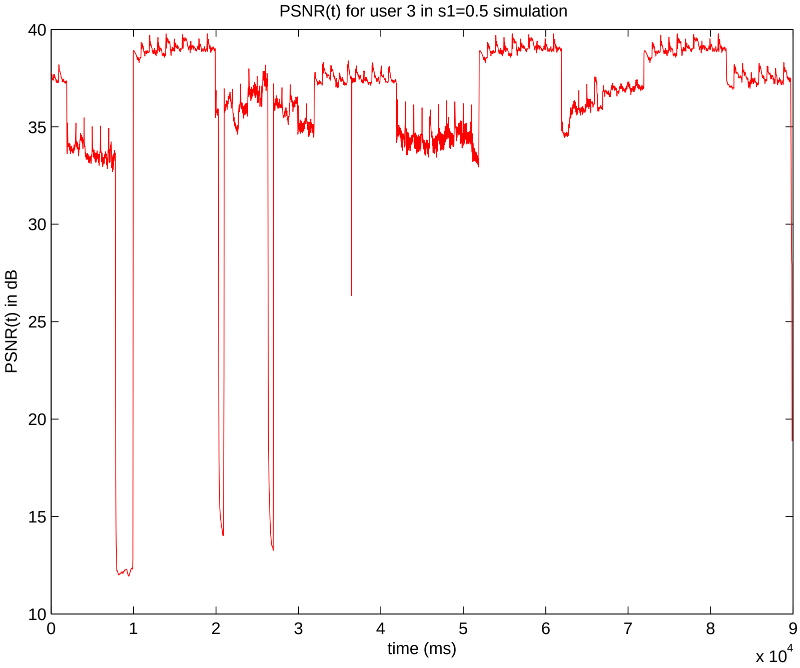

Figure 4.2: Y-PSNR trace for video user number 3 for CAA.

The best results are achieved for the CAA scheduler with $S_1 = 0.5$ in terms of both performance gain and fairness. It could be noticed that performance improve for decreasing values of S_1 because more transmission rate is assigned to a single user. However, below 0.5 the scheduler loses both fairness and efficiency. Moreover, since user number 2 suffers from large pathloss, the system is not able to provide enough transmission rate during the intervals of peak video rate, leading to large Y-PSNR degradation for both scheduling strategies. In the next figures parameter $S_1 = 0.5$ in the CAA scheduler will be considered.

Fig. 4.2 contains a trace of the frame-wise Y-PSNR for video user 3, to illustrate the behavior of the instantaneous quality experienced by a video user depending on channel fluctuations. It can be observed that quality degradation is never soft: when the system, due to bad channel conditions or sudden increase of the video bit rate, is not able to assign enough transmission rate to the video flow, the quality drops to very low Y-PSNR values.

In Fig. 4.3 the outage rate of video users is shown for the CAA and the MaxTP scheduler. As expected, thanks to the cross-layer implementation which takes into account also application-side information, the CAA scheduler results in less outage. In fact, the proposed strategy tries to serve video packets before the deadline expires, and not only waiting the moment when channel quality is at its best.

Nevertheless, it is worth evaluating how the cross-layer strategy performs with respect to UDD users compared to MaxTP in terms of average throughput and average delay, respectively in Figs. 4.4 and 4.5. It can be seen that while CAA preserves the throughput of these users, the average delay is increased compared to MaxTP. This is the price to be paid for serving video users taking into account their packet deadlines.

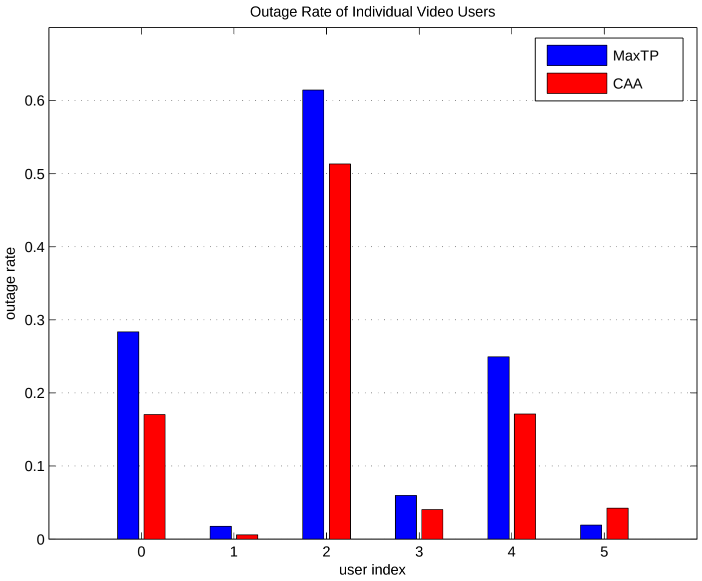

Figure 4.3: Video outage rate for CAA and MaxTP.

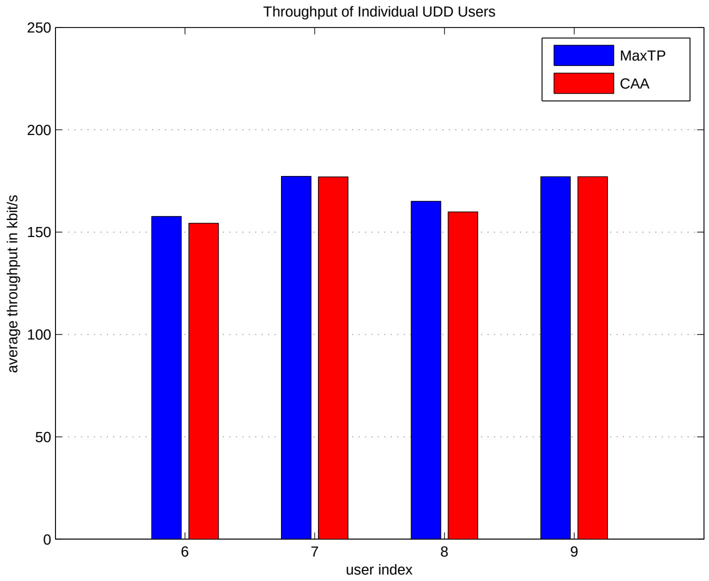

Figure 4.4: UDD average throughput for CAA and MaxTP.

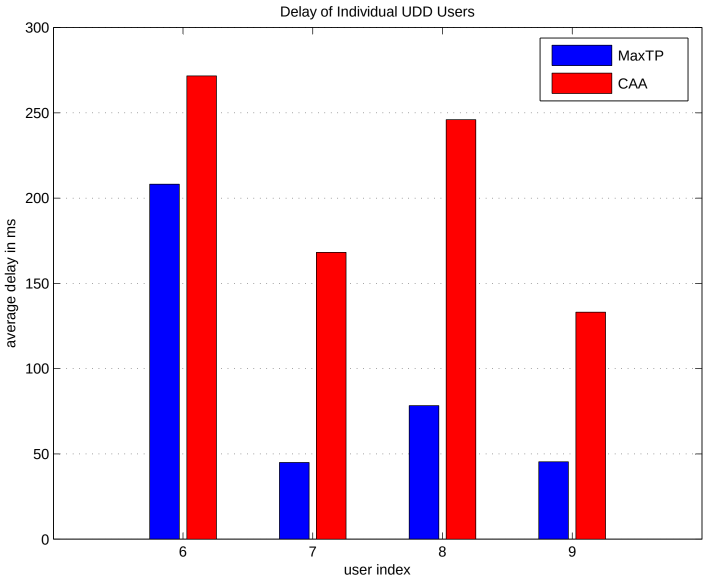

Figure 4.5: UDD average delay for CAA and MaxTP.

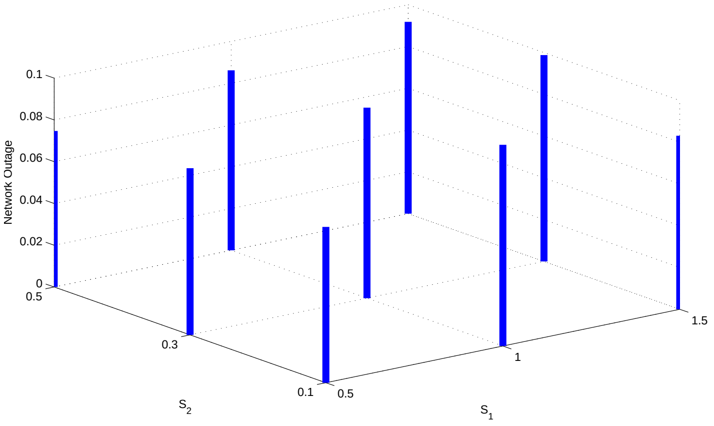

Figure 4.6: Video outage rate depending on S_1 and S_2 for CAA.

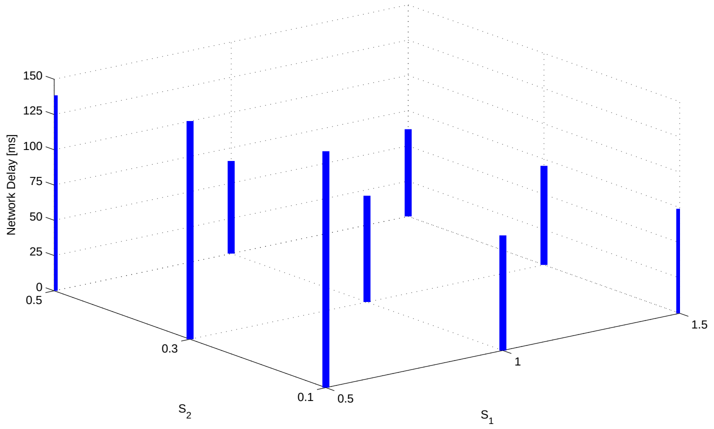

Figure 4.7: UDD delay depending on S_1 and S_2 for CAA.

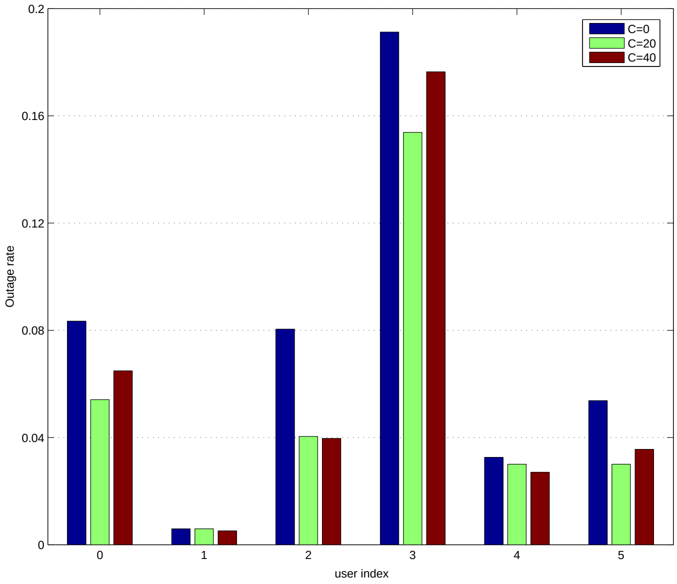

Figure 4.8: Video outage rate depending on C for CAA.

In order to perform a more accurate parameter optimization, in Fig. 4.6 and 4.7, the impact of different settings of the couple of thresholds S_1 and S_2 in the proposed CAA scheduler is evaluated on the outage rate for video users and delay for UDD users. From the figures, it can be observed that the best parameter combination is different for both types of service. However, since there is no hard delay constraint imposed by UDD users, while outage of video is critical to the end user, the combination $S_1 = 0.5$ and $S_2 = 0.1$ is selected.

Now having fixed the best values for S_1 and S_2, parameter C in Eq. 4.2.1 could be optimized. In Fig. 4.8 the outage rate of each video user is depicted for three values of C for a different set of user positions with respect to previous Figures. It can be seen that C should be different from 0 to get decent performance, and the best choice is $C = 20$ TTIs.

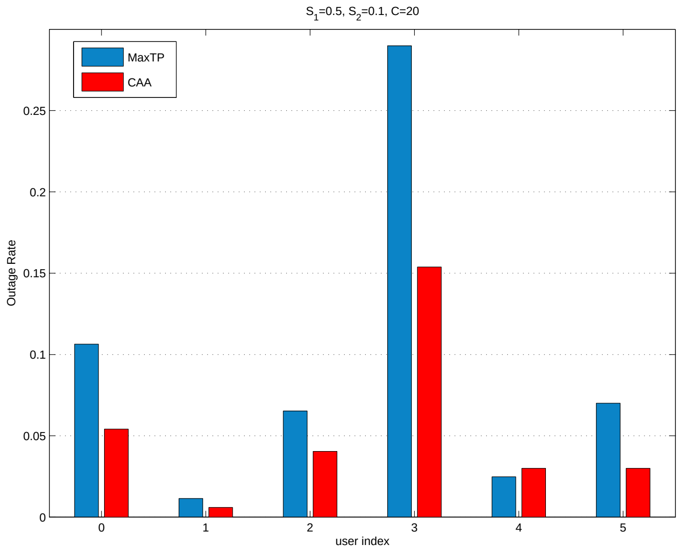

Figure 4.9: Video outage rate for CAA and MaxTP.

CAA and MaxTP Performance Comparison

Having found the optimal set of parameters $S_1 = 0.5$, $S_2 = 0.1$, and $C = 20$, the CAA scheduler is compared to the reference MaxTP scheduler. Observation of the outage rates of each video user in Fig. 4.9 shows that for user 0 and user 3, an outage threshold of 10% is exceeded by MaxTP, while CAA is able to maintain decent service for 5 out of 6 video users. However, user 3 suffers from large pathloss, hence, the system is not able to provide enough transmission rate during the intervals of peak video rate, leading to large Y-PSNR degradation for all investigated strategies.

Finally, performance of UDD users can be evaluated: while the achievable average throughput shown in Fig. 4.10 is comparable for both schedulers, the resulting average delay depicted in Fig. 4.11 is much lower for MaxTP, as already discussed.

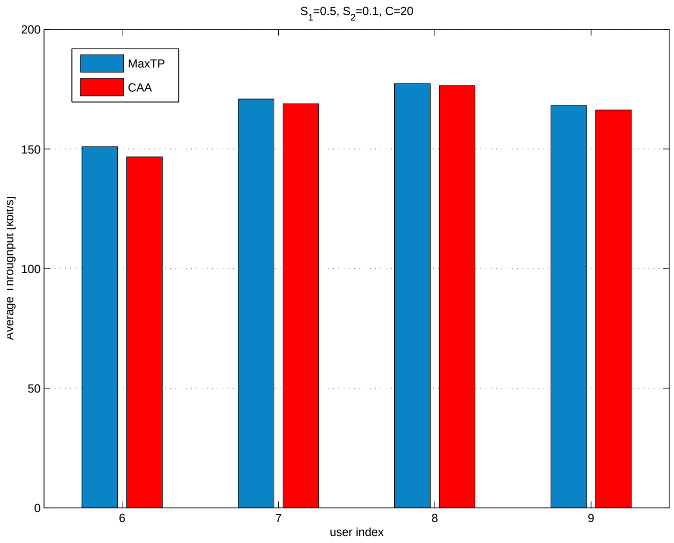

Figure 4.10: UDD average throughput for CAA and MaxTP.

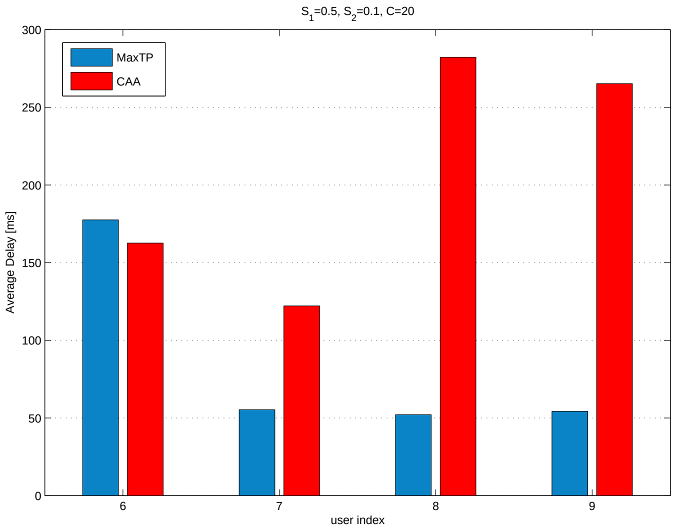

Figure 4.11: UDD average delay for CAA and MaxTP.

As a conclusion of these preliminary results, a trade-off takes place when selecting an optimal set of design parameters for a mixture of different service classes: if the primary focus is on maintaining a decent visual quality for a sufficiently large number of video users, UDD users receive lower priority during the scheduling process. However, compared to a purely throughput-oriented scheduler, at least almost the same average throughput for UDD users can be achieved, while delay performance are sacrificed. Nevertheless, the benefit is a larger number of satisfied video users, which are expected to contribute more to the overall revenue of system providers.

As a final remark, while CAA allows to incorporate application-specific QoS requirements in the decision, it does not guarantee that a certain QoS level is maintained for each user. This is due to the opportunistic principle assumed, which prevents the computation of exact theoretical performance bounds. However, this is also true for MaxTP, and the complexity of such computation is prohibitive in case of cross-layer implementation due to the many interactions happening in the system.

4.2.2 Numerical Results: the Multi-Cell Case

In the following the same parameters presented in Section 4.2.1 are used, excepting the NRT cross-traffic model, which in this case is realistic FTP data as described in Section 3.4.3. Moreover, since in realistic environment intercell interference coming from adjacent cells can not be counteracted, this is taken into account and its impact on the system will be assessed. Finally, having changed the cross-layer traffic model, the coefficient to be used in Eq. 4.2.1 have been updated. In particular, the value of coefficients W, A, B are given in Table 4.2.

The aim of this Section is to evaluate the impact of resource allocation strategy,

Table 4.2: Values of coefficients W, A, B.

	TS=RT			TS=NRT		
CS	W	A	B	W	A	B
a)	1	200	1	5	-5	-0.5
b)	0	210	2.1	5	-10	0.1
c)	0	200	2	5	-10	0.1
d)	0	0	2	0	0	0.1

traffic load and interference level on system performance. In this case the cross-layer CAA strategy will be compared with both the MaxTP and WFS [73] traditional schedulers, in order to have a comparison with a purely opportunistic and a fairness-oriented strategy. For the last strategy, since it considers only two possible channel states, it has been decided to state a and b as "good channel" and, as opposite, c and d as "bad channel" for video users, whereas for the FTP data only state a is considered as good, since this application is more error-sensitive. Finally, performance figures are evaluated over 25 scenarios, each characterized by different channel configurations regarding user position, shadowing and fading, in order to obtain results averaged over the statistical fluctuations due to both channel configurations and fast time-variant channel conditions. The number of scenarios has been proven to be sufficient.

The Impact of the Resource Allocator

First of all, the impact of the resource allocation strategy on the different scheduling policies under investigation is evaluated. Results are related to the case without interference, with mixed traffic composed of 6 video and 4 FTP users. In Fig. 4.12 the Cumulative Distribution Function (CDF) of the outage rate is plotted depending on the scheduling and the resource allocation policies. It can be noticed that, since the traffic load is smaller than the system capacity, the scheduling policy implemented

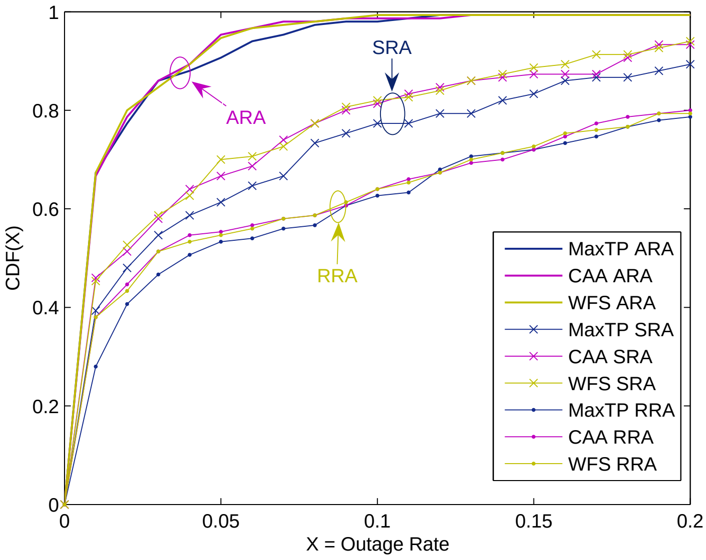

Figure 4.12: CDF of video outage rate depending on scheduling and resource allocation.

Table 4.3: Maximum TBLER experienced by 90% of FTP users.

Scheduler	ARA	SRA	RRA
MaxTP	0.04	0.05	0.08
CAA	0.04	0.04	0.05
WFS	0.04	0.05	0.06

is not determinant: lines related to the same resource allocation policy are almost superimposed. However, an allocation policy implementing link adaptation is indeed fundamental to meet the application requirements.

The same considerations can be performed for FTP users evaluating the CDF of the Transport BLock Error Rate (TBLER). In Table 4.3 the maximum TBLER experienced by 90% of FTP users is reported depending on the scheduling and allocation strategies. The scheduling strategies show almost the same performance fixing the resource allocation policy.

Table 4.4: Maximum outage rate perceived by 90% of video users.

z (dB)	MaxTP	CAA	WFS
∞	0.05	0.04	0.04
40	0.09	0.07	0.07
30	0.30	0.29	0.29
20	0.76	0.76	0.75

The Impact of Intercell Interference

Fixing the ARA strategy and the traffic previously described, in Table 4.4 the impact of interference on scheduling policies is reported. Being z the median signal to interference ratio at the cell border, the maximum outage rate perceived by 90% of video users depending on z and scheduling policy is given. It is worth specifying that the interfering channel is also affected by log-normal shadowing and Rayleigh fading.

The Impact of Traffic Load

Setting $z = 40$ dB and the number of FTP users at 4, the impact of the video traffic load on scheduling policies is plotted in Fig. 4.13. With 9 video users, the system behaves almost like with 6 video users for CAA and WFS, since the buffer management strategy discards the unnecessary packets guaranteeing good performance. On the contrary, MaxTP performance quickly degrade, since no mechanism considers the delay sensitiveness of the application, in fact the lead and lag counters are an implicit way to manage packet deadlines. Finally, only the cross-layer approach implemented in CAA can cope with a heavily loaded system such as the one with 12 video users. Nevertheless, the worst technique in this case is WFS, since it misses the users with the best channel quality trying to preserve fairness in very unfavorable conditions.

As a final remark on this Section, it can be noticed that results show that, due

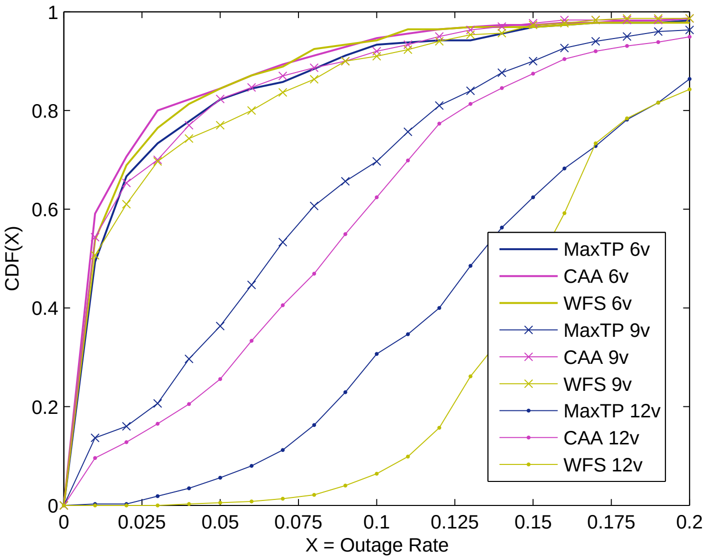

Figure 4.13: Impact of traffic load on different scheduling policies.

to the large number of parameters to be considered, the three strategies give almost the same performance in case of non-heavy loaded systems. Nevertheless, a significant sensitivity to the resource allocation strategy has been highlighted. In case of heavy loaded system, the exploitation of the cross-layer approach implemented in the proposed scheduler guarantees good performance.

4.3 A Complexity-Reduced Cross-Layer Channel and Application Aware Scheduler

In the following, a new cross-layer channel- and application- aware scheduling algorithm is proposed inspired by [81] and CAA. The new strategy has been designed having in mind that the algorithm in [65] is dependent on a large number of parameters that make algorithm optimization a very complex task. Unlike the one presented in Section 4.2, owing to the design approach used, parameter optimization can be performed through a conceptual approach rather than in a blind exhaustive and complex way. This new algorithm will be compared firstly to the one presented in Section 4.2, and then to well known channel-aware and -unaware scheduling strategies, like EDF, MaxTP, WFS. The proposed cross-layer scheduling algorithm shows the same performance of the one presented in Section 4.2 while presenting complexity reduction, and it significantly outperforms simpler channel-aware and -unaware techniques in case of heavily loaded systems. Moreover, a formal description of the computational complexity of this algorithm is provided, and compared to some schemes proposed in the literature. It is shown that the proposed algorithm either presents better performance or the same amount of computations while complexity is significantly lower.

The CAA scheduling algorithm proposed in Section 4.2 has so many parameters (W, A, B, C, S_1, S_2) that it is difficult to be optimized for each different application, since the optimization space is very large. Thus, it is opportune to propose a new priority function characterized by a reduced set of parameters, while trying to preserve performance behavior.

First of all, the new proposed scheduling algorithm preserves the traffic organization into two classes, since it is recommendable to serve video traffic first due to its delay sensitiveness. Then, the definition of T_D is harmonized for both traffic classes: a parameter T_{SQ} defined as the time spent in queue, which is a metric applicable to any traffic type, is introduced. Moreover, the number of possible channel states is reduced to three, according to only two thresholds T_1 and T_2 as follows:

g) γ is above T_1: good channel state;

i) γ is between T_2 and T_1: intermediate channel state;

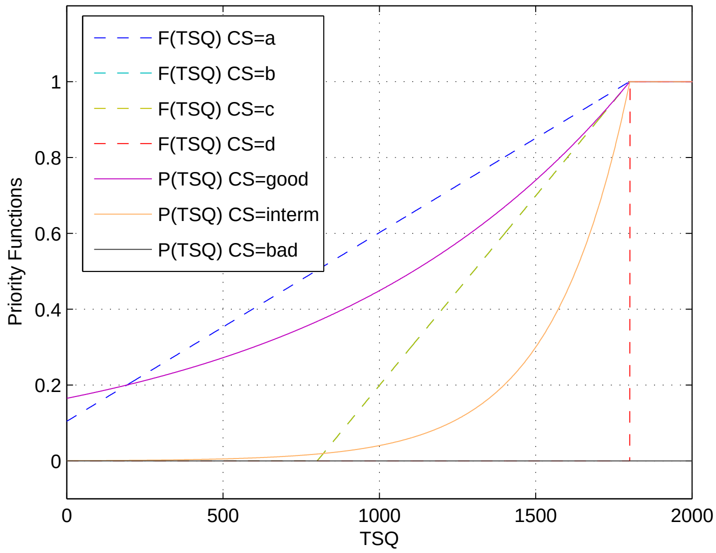

Figure 4.14: Comparison between CAA and CAA-E priority functions.

b) γ is below T_2: bad channel state.

Finally, two different priority functions, one per traffic type, are introduced. For RT traffic an exponential function is used:

$$P_{RT}(T_{SQ}, CS) = \begin{cases} \kappa(CS)e^{Q(T_{SQ},CS)}, & T_{SQ} \geq \tau, \\ \kappa(CS), & T_{SQ} < \tau, \end{cases} \tag{4.3.1}$$

with:

$$Q(T_{SQ}, CS) = -\frac{\delta_{\text{init}} - (T_{SQ} + \tau)}{\varphi(CS)}, \tag{4.3.2}$$

where $\kappa(CS)$ is a constant value equal to 0 when CS is bad, 1 when CS is good or intermediate. This aspect will be discussed further in Section 4.3.2. Parameter τ introduces a fixed artificial shortening of the time to deadline as C in Eq. 4.2.1, which is preserved since it has be proved to be really beneficial, and is computed as the maximum packet length divided by the average number of allocable bits per user. Parameter δ_{init} was defined in Section 3.4.3. $\varphi(CS)$ is a constant value depending on the channel state: in particular it is computed for good and intermediate channel states. Its impact will be discussed further in Section 4.3.2. In Fig. 4.14 a comparison between $F(T_D)$ for the RT service and $P_{RT}(T_{SQ}, CS)$ is reported. In this figure $\varphi(CS)$ is 1000 in case CS is good, and 250 in case CS is intermediate.

In case of NRT applications, a very simple priority function is defined as:

$$P_{NRT}(T_{SQ}, CS) = \begin{cases} \vartheta, & CS = g, \\ 0, & CS = i \quad or \quad CS = b. \end{cases} \tag{4.3.3}$$

where g stands for “good”, i for “intermediate” and b for “bad”.

So, according to these definitions, the only parameters to be optimized in such algorithm, which will be denoted as Channel- and Application-Aware with Exponential Function (CAA-E), are $\varphi(CS)$, T_1, T_2, and ϑ. This will be done through some considerations as shown in the following.

4.3.1 Discussion on Selection of Scheduling Parameters

Unlike in CAA, where the selection of scheduling parameters (W, A, B, C, S_1, S_2) was performed in a completely heuristic way via simulation, with CAA-E some considerations on proper parameter selection can be performed before simulation validation, thanks to the reduced number of parameters.

In fact, the rationale behind the choice of Eq. 4.3.1 and Eq. 4.3.3 is the following: for RT applications it is desirable that the larger the time spent in queue T_{SQ}, the larger the priority function. So, an increasing function should be selected. Obviously, also Eq. 4.2.1 is increasing if T_D is replaced with $T_{SQ} = \delta_{\text{init}} - T_D$, but Eq. 4.2.1

is piecewise and depending on W, A, and B, whereas the exponential function in Eq. 4.3.1 actually depends only on $\varphi(CS)$, in Eq. 4.3.2. Moreover, it is desirable that the better the estimated channel conditions, the larger the priority function, *i.e.*:

$$P_{RT}(T_{SQ}, g) > P_{RT}(T_{SQ}, i) > P_{RT}(T_{SQ}, b), \quad \forall T_{SQ}, \tag{4.3.4}$$

which is surely verified in case of bad channel conditions, since the priority function is 0, and in the other cases provided that $\varphi(CS)$ is suitably defined. The NRT function is even simpler, since it is a constant value different from 0 only if good channel state is estimated, due to the error-sensitiveness of NRT applications. Then, the value of ϑ is selected as follows:

$$P_{RT}(T_{SQ}, g) > P_{NRT}(T_{SQ}, g) \quad \forall T_{SQ}. \tag{4.3.5}$$

So, provided that $\varphi(g)$ in Eq. 4.3.2 can be fixed just in such a way that $P_{RT}(T_{SQ}, CS)$ is different from 0 for each value of T_{SQ}, the whole optimization problem of the scheduling algorithm is reduced to the choice of the following parameters:

- $\varphi(i)$ if an intermediate state is defined, smaller than $\varphi(g)$ to verify Eq. 4.3.4;
- ϑ, smaller than the minimum value of $P_{RT}(T_{SQ}, g)$ to verify Eq. 4.3.5;
- T_1;
- T_2 if an intermediate channel state is defined, smaller than T_1 to verify Eq. 4.3.4.

To sum up, in case of the CAA strategy proposed in Section 4.2, six parameters, namely, W, A, B, C, S_1, S_2, should be optimized, whereas in case of the CAA-E proposed in this Section, four constrained parameters, namely, $\varphi(i)$, ϑ, T_1, T_2, should be optimized in case the intermediate state is defined, and only two, namely, ϑ, T_1, otherwise.

Finally, the scheduling algorithm performs the following steps:

- for each proposal the priority metric $P(T_{SQ}, CS)$ is evaluated according to the relevant type of service. Then all proposals, regardless of the type of application, are ranked in decreasing order;
- the proposal with the largest value of $P(T_{SQ}, CS)$, regardless of the type of service, is scheduled.

4.3.2 Numerical Results

Sectorized cells are taken into account and it is assumed that the interference experienced by the target cell is generated by other cells not interfered by the target cell. The received interference power is computed by considering the transmit power coming from users belonging to a previously simulated neighboring cell, affected by fixed interferer pathloss, log-normally distributed shadowing and multipath Rayleigh fading. The median Signal-to-Interference Radio (SIR) at cell border is equal to 40 dB. About air interface, channel, buffer management and applications, the same parameters used in Section 4.2.2 are considered. In the following, performance figures are evaluated over 25 scenarios, each characterized by different channel configurations regarding user position, shadowing and fading, in order to obtain results averaged over the statistical fluctuations due to both channel configurations and fast time-variant channel conditions.

For the channel- and application- aware scheduler with exponential function, φ, T_1 and T_2 will be evaluated in the following, whereas τ is computed as the ratio of the

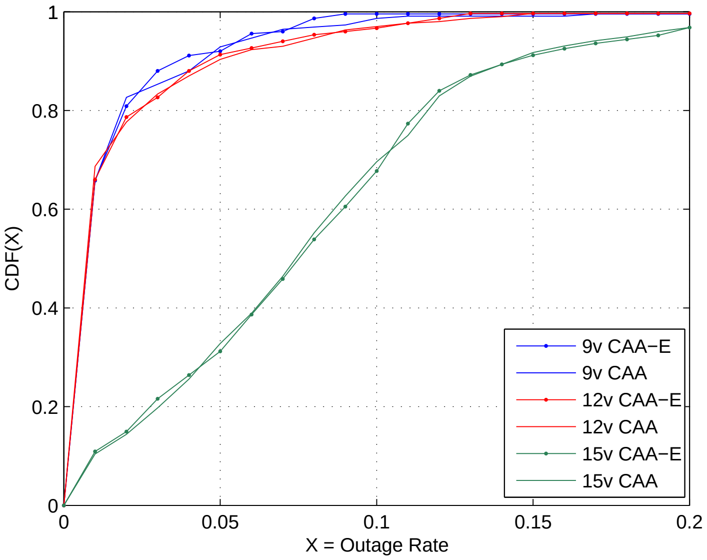

Figure 4.15: CDF of the video outage rate for CAA and CAA-E depending on traffic load.

maximum video packet size, cautiously equal to 55 kbits[2], over the average number of allocable bits per user, which is 5760 bits. Thus, τ is 20 TTIs.

First the performance achieved by the proposed scheduling strategy with the one introduced in Section 4.2 are compared. In Fig. 4.15, the CDF of the outage rate perceived by video users with ARA over 25 scenarios is plotted. In particular the number of video users spans from 9 to 15 and 4 FTP users have been also simulated. It can be noticed that, in spite of the significant reduction of the number of parameters in the new algorithm, it basically performs like the previous one. From now on, CAA will not be investigated any longer and, if not differently specified, the following parameters will be considered: $T_1 = 0.5$, $T_2 = 0.3$ and $\varphi = 250$. Such parameters have been selected as optimal choice after several trials in the scenario considered.

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[2] Video packets can be even larger than 50 kbits [145].

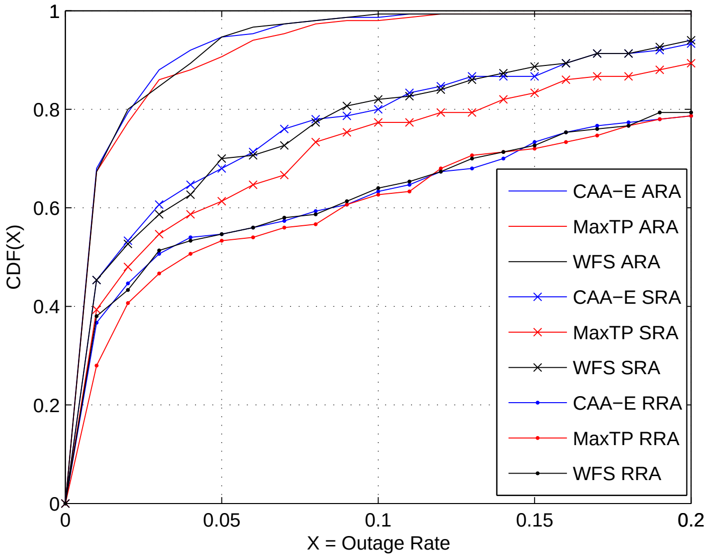

Figure 4.16: CDF of the video outage rate depending on scheduling and resource allocation with mixed traffic.

The Impact of the Resource Allocator

Now the outage rate perceived by video users without considering interference will be investigated to evaluate the impact of the resource allocation strategy. Both homogeneous traffic composed of 6 video users and mixed traffic with the addition of 4 FTP users have been considered. In Figs. 4.16 and 4.17, the CDF of the outage rate perceived by video users is plotted for different scheduling algorithms and resource allocation policies. It can be noticed in both figures that also with CAA-E, since traffic load is smaller than system capacity, the scheduling policy implemented is not determinant; in fact, curves related to the same resource allocation policy are in most cases superimposed. However, the allocation policy, even without traffic load excess, is indeed fundamental to allow a large number of users to meet the application requirements. In fact, ignoring users with average channel conditions

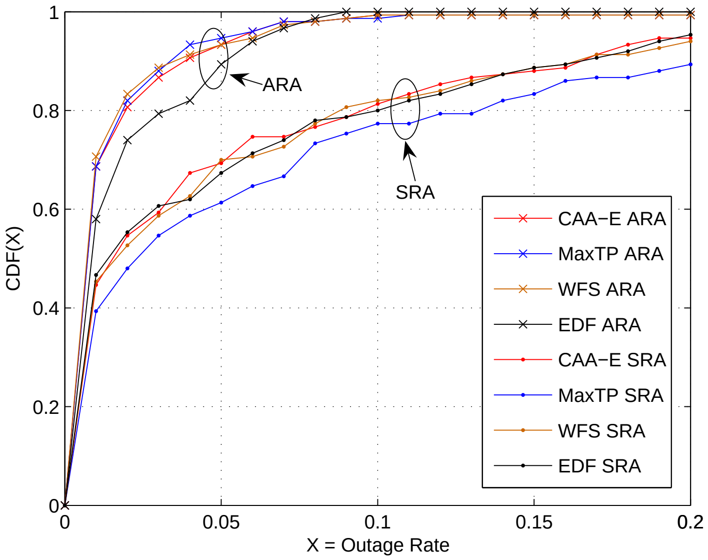

Figure 4.17: CDF of the video outage rate depending on scheduling and resource allocation with video traffic only.

good enough to perceive satisfying performance almost always, the other users are significantly helped by the allocation policy. Thus, the lines shown in the figures rise slower as the resource allocation becomes less adaptive. So, it can be concluded that the link adaptation performed by ARA plays a key role in handling the channel fluctuations and, hence, in guaranteing performance levels. In fact, by looking for example at Fig. 4.16, where mixed traffic composed of 6 video and 4 FTP users is considered, and fixing the maximum outage rate at 0.05, the ARA policy guarantees the satisfaction of more than 90% of video users; this value decreases to only 70% and 50% in case of SRA and RRA, respectively. On the contrary, by looking at the performance experienced by 80% of users, ARA guarantees a maximum outage rate equal to 0.025, whereas SRA and RRA are not able to achieve outage rates beyond 0.1 and 0.2, respectively. Moreover, in case of video users only as in Fig. 4.17, EDF

Table 4.5: Maximum TBLER experienced by 90% of FTP users depending on scheduling and resource allocation.

% of Users	Scheduler	ARA	SRA	RRA
90	MaxTP	0.04	0.05	0.08
	CAA-E	0.04	0.05	0.06
	WFS	0.04	0.05	0.06

Table 4.6: Maximum outage rate perceived by 90% of video users for different scheduling depending on interference.

% of Users	z dB	MaxTP	CAA-E	WFS
90	∞	0.05	0.04	0.04
90	40	0.09	0.06	0.07
90	30	0.30	0.28	0.29
90	20	0.76	0.74	0.75

shows the worst performance, leading to the conclusion that channel-awareness is fundamental in a wireless environment.

Similar considerations can be derived for FTP traffic sources after the evaluation of the CDF of the TBLER. In Table 4.5 the maximum TBLER experienced by 90% of FTP users is reported depending on different scheduling and resource allocation policies. It can be noted that performance are practically insensitive to scheduling strategy but show a non-negligible dependence on the resource allocation one.

The Impact of Intercell Interference

Now focus will be moved to the impact of interference on the scheduling policies, assuming the ARA strategy, looking at Table 4.6. Defining z as the median signal-to-interference ratio at cell border, directly related to the reuse distance, the maximum outage rate perceived by 90% of video users is computed as a function of z. It can be noted that the system is very sensitive to interference, which has to be properly limited

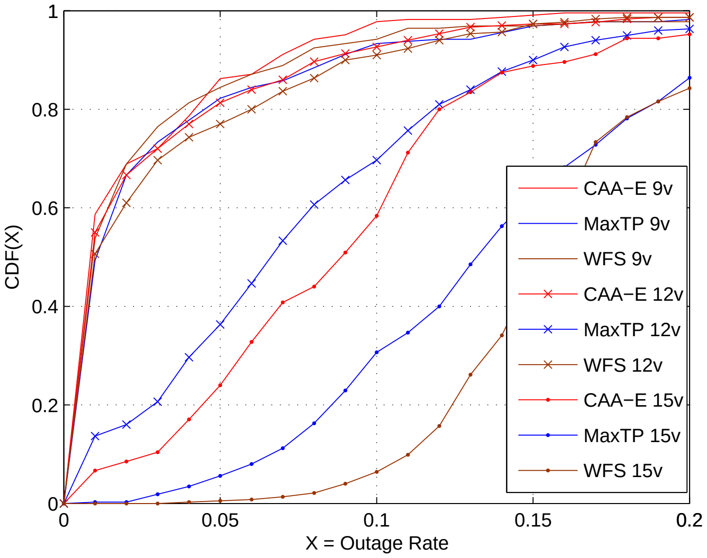

Figure 4.18: Impact of traffic load on the performance of different scheduling policies.

through a channel reuse method, as already highlighted for CAA in Section 4.2.2.

The Impact of Traffic Load

In Fig. 4.18, by setting $z = 40$ dB and the number of FTP users at 4, the impact of the video traffic load on scheduling policies is evaluated. With 9 video users, the system behaves similarly to the one with 6 video users. With 12 video users CAA-E and WFS show almost the same performance, since the buffer management strategy discards the unnecessary packets and guarantees good performance. On the contrary, the MaxTP performance quickly degrades, since no mechanism takes into account the delay sensitivity of the application, as already mentioned for the comparison with CAA. Finally, only the cross-layer approach implemented in CAA-E can cope with a heavily loaded system such as the one with 15 video users. Nevertheless, the worst technique in this case is WFS, since it misses users with the best channel quality

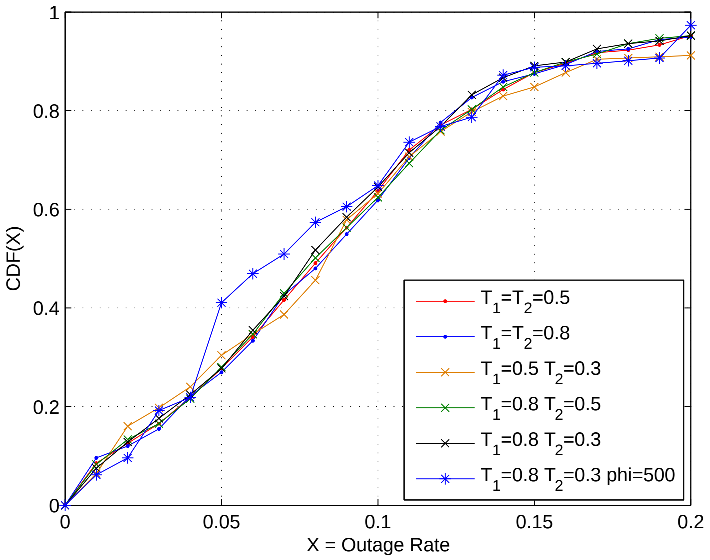

Figure 4.19: CDF of the outage rate for 15 video users depending on scheduling parameters.

trying to preserve fairness in very unfavorable conditions.

Sensitiveness to Scheduling Parameters

In Fig. 4.19 the CDF of the outage rate perceived by 15 video users as a function of the scheduling parameters in case of CAA-E is shown. It can be seen that the system is not sensitive to parameters variation, which means that the dominant aspect in the scheduling strategy is given by the exponential behavior of the function. The only line which significantly differentiates from the others is the one related to parameters $T_1 = 0.8$, $T_2 = 0.3$ and $\varphi = 500$, which means that it is beneficial for the system to have 3 different channel states, and the intermediate channel state is better exploited in case it is given with a high priority.

Table 4.7: Average value of the Jain's index for both Y-PSNR and number of TBs transmitted through CAA-E depending on traffic load.

X	video user number	CAA-E
Y-PSNR	9	0.999
	12	0.999
	15	0.998
TB_{Tx}	9	0.995
	12	0.992
	15	0.992

Fairness Evaluation

At this stage, it is interesting to evaluate the fairness index for video users achieved by CAA-E, in order to check whether good resource allocation is performed with or without guaranteeing fairness. To this aim, the Jain's index defined in Section 3.7 averaged over 25 scenarios is computed, *i.e.*:

$$\overline{J(X)} = \frac{1}{N_s} \sum_{i=0}^{N_s-1} J_i(X) \tag{4.3.6}$$

where $J_i(X)$ is the Jain's index calculated either over the average Y-PSNR of each video user or over the number of Transport Blocks (TB) transmitted in scenario i, and N_s is total number of scenarios equal to 25. These two evaluations have been performed to ensure that fairness is preserved at both application and physical layer. In Table 4.7 it is shown that CAA-E guarantees excellent fairness thanks to the cross-layer approach. It is also worth noting that this good level of fairness is achieved without the need of the additional leading and lagging counters needed in WFS.

Computational Complexity

At this point, it is worth discussing the complexity of CAA-E with respect to algorithms that jointly handle scheduling and resource assignment. According to previous considerations, MaxTP belongs to such class; beside that, the technique proposed in [41] characterized by the same property, has been also selected for sake of comparison. The number of operations performed by CAA-E, MaxTP and the scheme in [41] have been evaluated as done in [41]. In the latter case, subcarriers are assigned separately to users; therefore, to make a fair comparison, CAA-E and MaxTP have been considered in the particular case of GoFs composed of single subcarriers.

For sake of comparison, according to the notation used in [41], K and N are now respectively the number of users and subcarriers. In [41], the proposed scheme has a complexity that is evaluated as $O(3KN + 2N^2)$. Following the approach used there to assess the complexity of CAA-E and MaxTP, it clearly appears that they have the same computational complexity, which can be estimated as $O(\sum_{i=1}^{K}[K-(i-1)]+[K-(i-1)][N-(i-1)])$. To make comparison simpler, an upper bound to the previous expression can be also provided: in the worst case, the complexity is $O(K(K+NK))$. As it is clear from the above expressions, the complexity is dominated in [41] by N^2, and in the proposed cross-layer algorithm (and in MaxTP) by K^2. However, the number of users K is usually significantly smaller than the number of subcarriers N_C. As a conclusion, CAA-E is clearly characterized by a reduced complexity with respect to the scheme proposed in [41]. This statement is also true for other papers from the literature presenting algorithms which are not separated into the two functionalities discussed in this paper, *e.g.*, [42] and [43]. Therefore, even if a general rule can not be formally defined, it can be stated that papers presenting algorithms which are not decomposed, are normally characterized by a complexity which is higher than CAA-E. A relevant exception to this, is the simple and widely known MaxTP technique, which has same complexity as CAA-E; on the other hand, CAA-E performance is better than MaxTP in some cases, and CAA-E is also more fair than MaxTP.

To quantify the computational complexity of CAA-E (and MaxTP) with respect to [41], two numerical examples are considered and the above expressions are evaluated: when $K = 3$ and $N_C = 64$, CAA-E has $O(386)$ while from [41] $O(8768)$ is obtained; with more users, like $K = 10$, this becomes $O(3410)$ and $O(10112)$ for CAA-E and [41], respectively.

Finally, the algorithm proposed in [41] has been implemented to compare the computational time of the three algorithms. Noting that, according to a statement in [41], the algorithm is computationally prohibitive for larger number of users, simulations have been run over a Pentium IV at 3 GHz setting $K = 3$ and $N_C = 64$. The following results were achieved to simulate 60 seconds of traffic flow: 115, 130, 146 seconds for MaxTP, CAA-E and [41], respectively. Clearly, the simulation time is affected by many procedures that have to be run, such as for the allocation of fading samples, the buffer management, et cetera, that do not depend on the complexity of the scheduling technique. Therefore, computational time is scarcely affected by it. On the other hand, the complexity of the algorithm is very relevant from the practical viewpoint, for its possible implementation into a real wireless network. Therefore, the above considerations on the evaluation of the computational complexity of CAA-E with respect to the benchmarks, should dominate the conclusions.

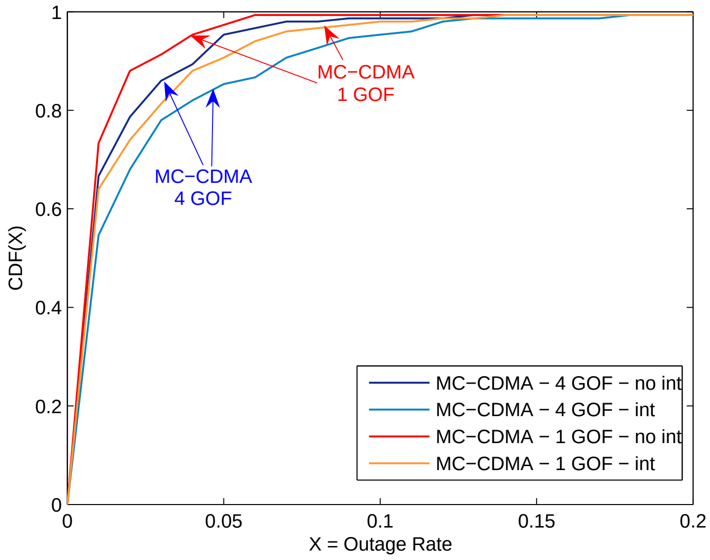

Figure 4.20: CDF of the video outage rate depending on the number of GoFs.

Impact of the Number of GoFs and Spreading Factor

As a final consideration, it is interesting to evaluate the impact of the number of GoFs and, hence, the spreading factor, on system performance.

In Fig. 4.20 the CDF of the outage rate perceived by 6 video users as a function of the number P of GoFs and, hence, the spreading factor, is shown in case of CAA-E scheduling combined with the ARA resource allocation. It can be seen that the MC-CDMA system with 1 GoF outperforms the case with 4 GoF both in presence and in absence of interference. This is due to the fact that with one GoF the channel fluctuations due to multipath fading are more averaged than in case of GoF equal to 4. Moreover, in presence of interference, its power is reduced by a factor $K = N_C/P$, as shown in Eq. 3.5.1. Hence, it can be concluded that it is more convenient to use the MC-CDMA system with the maximum allowed spreading factor.

Chapter 5

Cross-Layer Scheduling in a Multi-Carrier Emergency Network

Wireless ad hoc networks attract raising interest in research due to flexibility of application and deployment. For example, they can be of great relevant for emergency purpose. Moreover, cross-layer design is emerging as one of the most appealing approaches in network design. In this Chapter a dangerous area is considered where rescue teams enter and quickly deploy some monitoring devices, like cameras and sensors, equipped with wireless transceivers and able to send data to a sink that forwards the flows to a control unit where decisions are taken accordingly. Sensors send their data to some coordinator nodes through IEEE802.15.4. Then, both the coordinator nodes and the camera devices compete to access the radio channel assuming a MC-CDMA air interface is used by the sink.

The radio resource assignment problem will be addressed in the context of such a heterogeneous ad hoc network, organized in a hierarchical architecture, composed of IEEE802.15.4 sensor devices, their coordinators, mobile terminals conveying video streams, and sinks. What is interesting is that this scenario also fits to the paradigm of opportunistic networks, since the devices deployed by rescue teams are assumed to be able to find some pre-existing sensor network and to use it to get additional data from the environment. The proposed cross-layer scheduling strategy takes into account information coming from both physical and application layers. Results show that the cross-layer strategy significantly outperforms MaxTP, used as a benchmark, in case of video traffic, while preserving the same performance for IEEE802.15.4 traffic.

5.1 A 2-level Hierarchical Ad Hoc Network

5.1.1 Scenario

Wireless ad hoc networks are characterized by flexibility of application and deployment, supporting both single- and multi-hop transmissions [147]. Recently the ad hoc network paradigm has been applied to emergency scenarios [148], [149], [150]. In this Chapter a peculiar ad hoc network is considered. In case a terroristic attack occurs in an indoor environment, for example a high building or an airport, it could be of interest for the community to quickly deploy a certain number of fixed camera devices over each floor of the attacked area. Video streams could be used for monitoring the condition of the walls, *e.g.*, if they are going to collapse, or the number of people injured who could be saved through prompt medical cares. In this case it can be imagined that video streams are transmitted by every device of each floor to a special node, namely the sink, placed in a fixed position in the same floor. This node is enroled to collect all streams, elaborate and send them to a control unit placed

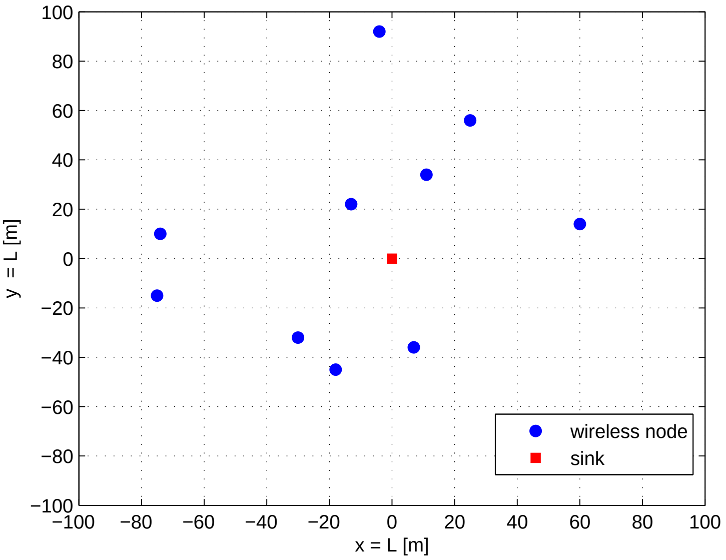

Figure 5.1: An example of nodes and sink deployment.

outside of the endangered building where some people, *e.g.*, firemen, doctors, . . . , take decisions according to the video data. Such particular ad hoc network could be considered also as a mesh network [151]. In such scenario, the problem of the multiple access in the lowest part of the hierarchy, *i.e.*, in the transmission from the nodes equipped with camera devices to the sink, is addressed. Due to the peculiarity of the application, a centralized cross-layer scheduling functionality is both recommendable and feasible. In fact, the strict constraints on delay and video quality, and the wireless channel variability, suggest a cross-layer implementation, and the particular deployment allows it. Also here, the case denoted in [32] as “back-and-forth” will be considered.

The focus here is on an indoor environment, for example a high building or an airport, composed of a square area of side L meters, where N wireless nodes are randomly and uniformly deployed, as depicted in Fig. 5.1. Each node is equipped with a camera device monitoring the environment, and a wireless transmitter conveys a video stream to a specific node, namely the sink, placed exactly in the center of the area. The sink has the role of gathering all the video sequences transmitted by the N wireless nodes. It is assumed that all nodes are equal and share the same set of radio resources. Due to the special characteristics of this part of the ad hoc network, scheduling can be performed in a centralized way at the sink, according to the information provided by all nodes through a control channel. In this scenario no interference is taken into account, since it is assumed that, due to the specific purpose of the network, *i.e.*, emergency, a bandwidth has been specifically devoted to the system. The remaining part of the network will not be addressed further in this Chapter, since it is assumed that the connection between sink and control unit is performed through a secure error-free link.

For air interface, channel and video traffic models, those described respectively in Sections 3.4.1, 3.4.2 and 3.4.3, are considered; moreover, the scheduling strategy proposed is also in this case applied in conjunction with the DDB buffer management described in Section 3.4.4.

5.1.2 Centralized Cross-Layer Scheduler over a Hierarchical Ad Hoc Network

In such innovative hierarchical heterogeneous ad hoc network, the centralized cross-layer scheduling algorithm presented in Section 4.3, and in the following denoted as Cross-Layer (X-Lay), is implemented. In fact, the main objective of this part of the Thesis is not introducing a new scheduling policy, but rather presenting how a cross-layer strategy properly designed behaves in a completely different network, even based on a different paradigm, like an ad hoc network, with respect to a cellular one.

In this network the priority function shown in Eq. 4.3.1 is implemented, because the kind of traffic flowing in the network is only real-time. Also in this case, the scheduling policy is combined with the ARA allocation strategy. However, there is a difference: in this case, anytime an estimation or computation of the SINR should be performed, this is replaced by the SNR, since no interference is taken into account for the reason explained in Section 5.1.1.

5.1.3 Numerical Results

A square area with side $L = 200$ m is considered. The same parameters presented in Section 4.2.1 are used but considering only video traffic. Simulation results are obtained considering different traffic loads by increasing the number of nodes until the maximum capacity allowed. Then, some optimization on scheduling parameters is performed. Results obtained through the cross-layer strategy will be compared to the MaxTP scheduling. Finally, performance are evaluated over 20 scenarios, each one characterized by different channel realizations, so that statistical fluctuations due to the time-variant channel and the usage of random numbers are averaged.

Before evaluating system performance, a rough estimate of the number of nodes supportable by an air interface with such characteristics as reported in Section 3.4.1 is performed. In particular, the maximum instantaneous channel capacity supported by the system, C^{max}, is computed as:

$$C^{max} = R_{b,RU}^{max} \cdot N_{SC}, \tag{5.1.1}$$

where $R_{b,RU}^{max}$ is the maximum bit rate supported by a single subcarrier. According to the parameters provided in Section 3.4, C^{max} is equal to 2.88 Mb/s. So, the maximum number of nodes N supported is equal to:

$$N \leq \frac{C^{max}}{R_v}, \tag{5.1.2}$$

which leads to $N = 15$ at most. Obviously, this is a rough estimation of the maximum number of nodes supported, since it takes into account ideal channel conditions, *i.e.*, it does not consider channel fluctuations due to shadowing and fading, which affect the actual channel capacity.

Performance will be considered in the following situations: half loaded system, which means 8 nodes supported, 80% loaded system, which means 12 nodes supported, and fully loaded system, which means 15 nodes supported.

Parameter Optimization

At this stage parameter optimization can be performed. First of all τ, which has the meaning of artificially shortening the deadline of each video packet in the priority function allowing the system to serve large video packets before their expiration, is computed as in Section 4.3.2: video traffic presents largely variable bit rates and packets even larger than 50 kbits may occur. Since the cross-layer algorithm allocates up to 64 RUs per node, 5760 bits are allocable at most. If a maximum packet size cautiously equal to 55 kbits is considered, and only half bits are allocable per node due to channel fluctuations, the number of frames necessary to serve the whole video packet is equal to 20 TTIs.

The impact of thresholds T_1 and T_2 on system performance is evaluated in Fig. 5.2. The CDF of the outage rate is evaluated for 12 and 15 nodes in two cases: the former,

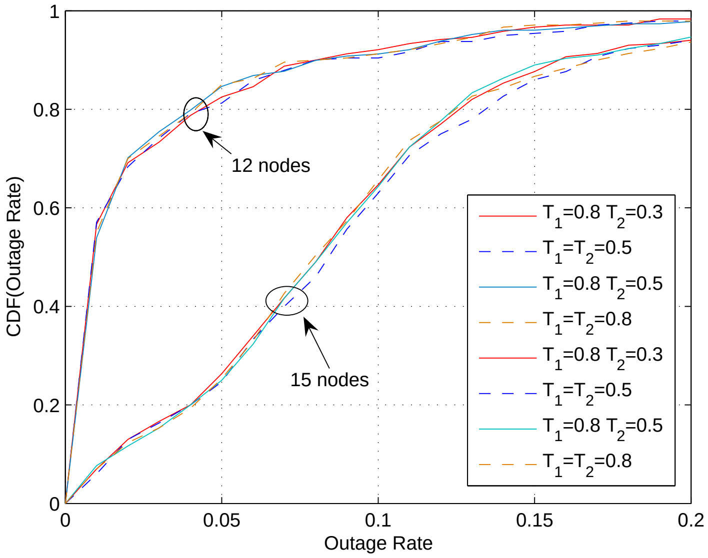

Figure 5.2: Impact of thresholds on X-Lay performance with 12 and 15 nodes.

two channel states are considered, hence, T_1 is equal to T_2 and different values of T_1 are tested; and the latter, three channel states are considered and different couple of T_1 and T_2 are tested. In case of both good and intermediate channel state $\kappa(CS)$ is 1, whereas for bad channel state $\kappa = 0$. $\varphi(CS)$ is 250 for the intermediate state. It can be noticed that the cross-layer strategy is not sensitive to the number of channel states and the relevant threshold values.

Fixing $T_1 = 0.8$ and $T_2 = 0.3$ the impact of parameter $\varphi(CS)$ in Eq. 4.3.1 on system performance is evaluated in Fig. 5.3. The CDF of the outage rate is evaluated in case of $\varphi = 250$ and $\varphi = 500$ for the intermediate state with both 12 and 15 nodes. The larger φ, the larger the priority for the intermediate channel state. However, also in this case no relevant performance gain is shown by any value of φ.

The last two figures proved that the cross-layer strategy is not sensitive to parameter adjustments in the priority function, since the dominant factor is the exponential

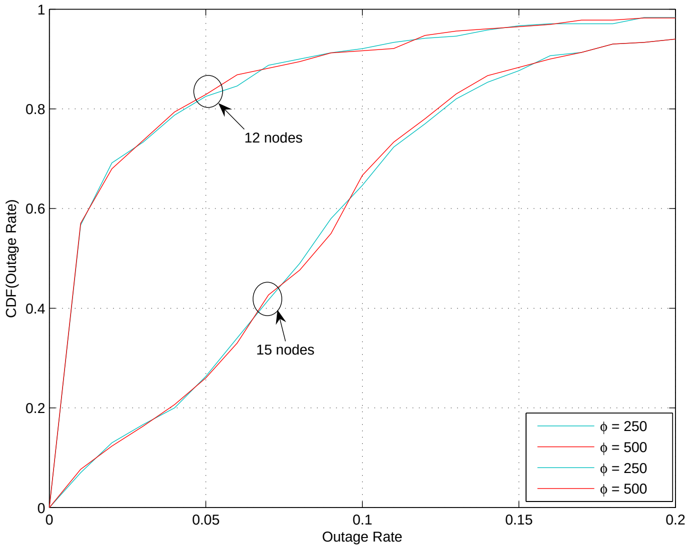

Figure 5.3: Impact of $\varphi(CS)$ for the intermediate channel state on X-Lay with 12 and 15 nodes.

behavior. So, not only a simple function was identified, but it is also not dependent on the particular set of parameters used, which means that optimization for this function is not critical.

The Impact of Traffic Load

The impact of traffic load on the cross-layer algorithm compared to the MaxTP will be now evaluated. In Fig. 5.4, the CDF of the outage rate as defined in Section 3.7 is plotted depending on the number of nodes deployed over the square area. Results for cross-layer scheduling are obtained considering $T_1 = T_2 = 0.5$, hence for only two channel states, $\kappa = 1$ and $\varphi = 1000$ for the good state, and $\kappa = 0$ for the bad one. It can be noticed that, when the system is half loaded, *i.e.*, 8 nodes, the scheduling policy is not really determinant: MaxTP and X-Lay strategies show almost the same

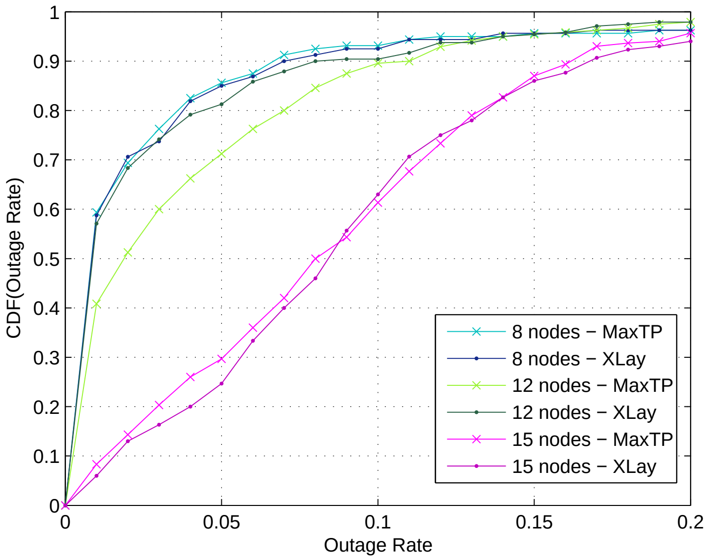

Figure 5.4: CDF of the outage rate depending on the number of nodes for X-Lay and MaxTP.

performance. This is due to the fact that not all RUs of the system are needed at each time frame, hence, many possibilities of allocation are available to each node.

On the contrary, when the system is heavily loaded, *i.e.*, 12 nodes, the cross-layer strategy shows relevant improvements on system performance. In fact, looking at outage rate equal to 0.05, X-Lay gain is 14% with respect to MaxTP. This is due to the fact that RUs can be temporarily scarce due to channel fluctuations, hence, an application-suited strategy better manages the available resources among nodes.

Finally, in case of fully loaded condition, *i.e.*, 15 nodes, X-Lay performs almost like MaxTP. Obviously, utilizing the system at its full capacity raises such issues that it is not recommendable. However, for sake of completeness, also such unfavorable condition has been evaluated. In particular, in case of outage rate equal to 0.05, MaxTP outperforms X-Lay of 4%, but with outage rate equal to 0.07 differences between the

Table 5.1: Average Jain's fairness index of the cross-layer scheduler.

Number of nodes	12	15
Jain's Index	0.994	0.991

two techniques are almost completely vanished. This is due to the fact that, when the system is overused, many video packets are served near to their expiration. Thus, only channel adaptivity remains, which means that X-Lay acts like MaxTP.

Fairness Evaluation

Table 5.1 reports the Jain's fairness index [146] computed on Y-PSNR basis and averaged over 20 scenarios, depending on the number of nodes for the cross-layer strategy. It can be seen that excellent fairness is guaranteed.

5.2 A 3-level Hierarchical Heterogeneous Ad Hoc Network

5.2.1 Scenario

The application framework considered now is an extension of the one presented in Section 5.1, and consists of a large building, where an emergency situation arises, due to, as an example, a bomb explosion or an accident involving the dispersion of chemical materials. Rescue teams enter the area and need to quickly deploy an ad hoc wireless network aiming at providing environmental information to a control unit located outside the building, where decisions are taken accordingly by the rescue team managers. The information to be provided consists of video flows, that could be used to monitor, *e.g.*, the condition of walls or the number of people injured, and in addition environmental data captured by sensors measuring, *e.g.*, temperature, chemical substances, et cetera, either to be distributed over the floors by the rescuers, or previously deployed for other reasons within the building.

To this aim, the rescuers use four types of device, all equipped with proper wireless transceivers: in particular, they (i) carry video cameras, (ii) disseminate sensors, (iii) deploy devices from now on denoted as sensing data coordinators or simply coordinators, able to collect information from the sensors, and (iv) place on each floor one wireless node, the sink, that gathers all data from the floor and provides them to the control unit outside the building.

The sink must be located in a proper position in order to establish a reliable link with the external control unit. So, this is the only device whose location should be properly planned. However, this link will not be investigated further.

Coordinators and cameras, randomly deployed or carried by rescuers, provide data flows to the sink through a suitable air interface able to efficiently manage the multiple access problem in such a heterogeneous and unplanned context. There is no need to exploit a standardized air interface, like WiMAX, UMTS, et cetera, owing to the specific characteristics of this application. Coordinators and cameras are assumed to transmit their flows to the sink through an MC-CDMA based system, implementing a proper controlled multiple access strategy to schedule video and sensor-generated flows. Time is organized in frames and at the beginning of each frame a proper scheduling mechanism assigns radio resources for the following frame to competing flows.

Coordinators collect data from sensors through a separate, low-complexity, low-data-rate wireless system. In this case, the adoption of a standard air interface, like *e.g.*, IEEE802.15.4, allows the opportunistic exploitation of the presence of sensors located in the building for other purposes: the coordinators might grab data acting as Personal Area Network (PAN) coordinators [141]. Such opportunistic use of existing networks was postulated by Lilien et al. in [50]. Furthermore, coordinators act as gateways: they are equipped with two different wireless transceivers, the former is IEEE802.15.4 compliant, and is used to gather data from sensors, whereas the latter is MC-CDMA based and is used to report previously collected data to the sink.

The use of different types of device, makes the scenario apparently complex. On the contrary, the use of a sink physically separated from the other devices is the key to make rescuers' operations independent from the need to check the presence of wireless connectivity, with the sink being the only element to be located with some care, *e.g.*, close to a window. All other devices will operate implementing a self-organized approach, and creating a heterogeneous ad hoc network with hierarchical topology: sensors send their data through IEEE802.15.4 to coordinators; the latter compete for access to the sink together with video cameras.

A scheduling strategy able to efficiently manage the access to the sink, given specific QoS requirements for the different types of data generated, should be designed. In particular, in the case of data coming from sensors, the QoS constraints, *e.g.*, maximum transfer delay, need to be considered in the context of a two-hop system where a random access mechanism is used at the first hop, considering that IEEE802.15.4 uses CSMA/CA, while a framed access strategy is assumed on the second hop. The larger the access time on the first hop, the more stringent the deadlines for scheduling the flow on the subsequent MC-CDMA link. In this scenario, a centralized scheduling functionality is both recommendable and feasible: the sink receives access requests

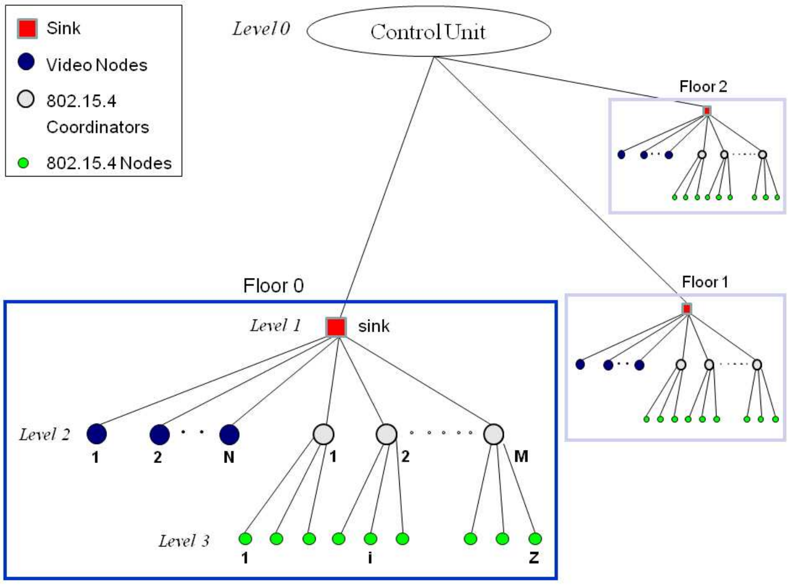

Figure 5.5: The hierarchical structure of the network for emergency scenarios.

and can schedule radio resource assignments at each frame.

The hierarchical network architecture considered is depicted in Fig. 5.5, and in particular the blue rectangle highlights the part of the network under investigation. The control unit at level zero is external to the building; the rescuers locate one sink per floor (level one), within the transmission range of the control unit; then, coordinators and cameras (level two) are randomly deployed: coordinators collect data from sensors (level three) through an IEEE802.15.4 air interface, using the Beacon-Enabled mode [141]. Coordinators act as gateways, forwarding the data gathered to the sinks at level one, through the MC-CDMA based system. Each coordinator has a radio link buffer to store the packets received from the sensors associated to it, before sending them to the sink. The association procedure between sensor nodes and coordinators defined by IEEE802.15.4 will be described later. The scheduling strategy is combined with buffer management, and in particular, for video traffic the DDB

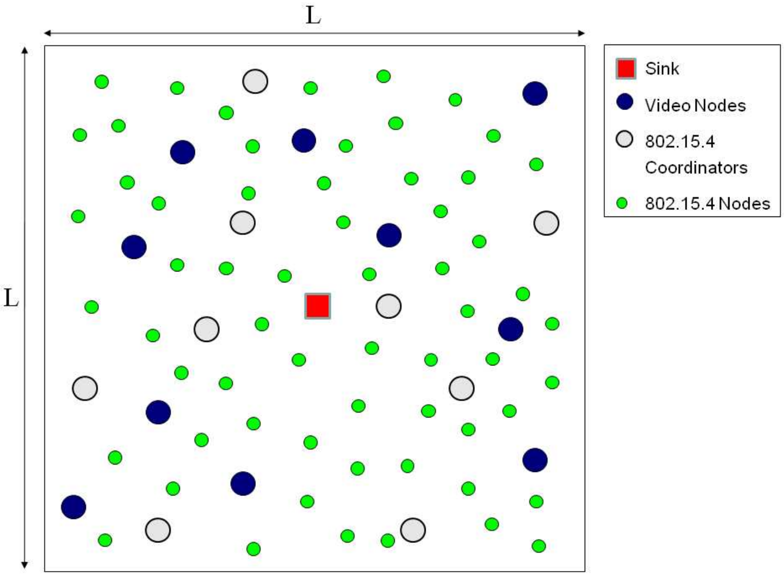

Figure 5.6: An example of devices and sink deployment.

strategy is considered, whereas for IEEE802.15.4 SFB is assumed, since all packets have the same priority and no selective packet removal can be applied, and buffer size N_{LB_s} is a parameter subject to optimization.

For the purpose of simulation settings, a square area of side L meters is assumed, where the sink is placed in the center; N wireless nodes equipped with a camera device, Z IEEE802.15.4 compliant nodes and M coordinators, are randomly and uniformly deployed. In particular Z is much larger than N and M. Thus, the sink has the role of gathering all video sequences transmitted by the N wireless nodes and all the data acquired by the M coordinators from the Z sensors. Fig. 5.6 shows a snapshot of the device deployment taken from a simulation.

All camera-equipped nodes and coordinators share the same set of radio resources, on a separate frequency band with respect to IEEE802.15.4 nodes. As far as the radio channel is concerned, two different models are used for the two separate air interfaces: with IEEE802.15.4, frequency selectivity and multipath fading are not issues since low bit rate, and hence narrowband, transmission, is considered, which means that only pathloss according to Eq. 3.4.1 and log-normal shadowing are considered; the MC-CDMA air interface is assumed to use a much larger frequency band, making multipath distortion a relevant aspect, which means that these two phenomena are superimposed to fading. MC-CDMA air interface is according to parameters set in Section 3.4.1, and video traffic to Section 3.4.3. Also in this case the cross-layer scheduling strategy is jointly implemented with the ARA resource allocator presented in Section 3.5.1, and no interference is taken into account for the same reason explained for the 2-level hierarchical ad hoc network.

5.2.2 IEEE802.15.4 Nodes and Coordinators Association

Traffic produced by sensing data coordinators depends on the number of IEEE802.15.4 nodes connected to each coordinator and on the specific protocol implemented at MAC sublayer. The number of IEEE802.15.4 nodes connected to each coordinator depends on the set up procedure according to which a link between an IEEE802.15.4 node and its coordinator is established. As already mentioned, wireless channel is affected by fluctuations. To select its own coordinator, each IEEE802.15.4 node measures the power received by each audible coordinator, performs a ranking in decreasing order of received power and, finally, chooses the first coordinator in the list. As stated in Section 5.2.1, the role of coordinators is to act as gateways for IEEE802.15.4 sensor nodes toward the sink.

As far as the MAC protocol is concerned, IEEE802.15.4 Beacon-Enabled mode is considered: the time axis is organized in superframes delimited by the transmission of

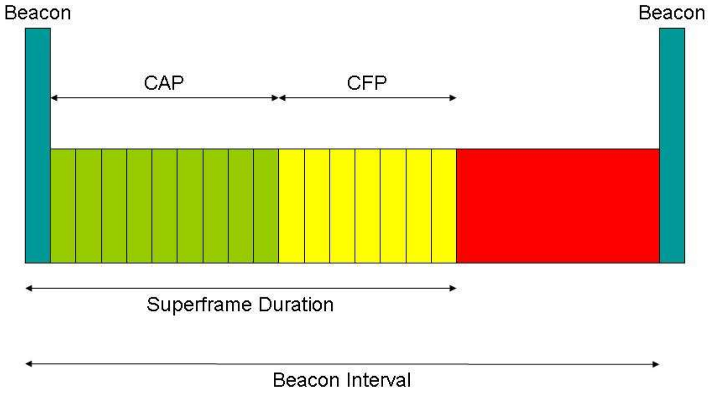

Figure 5.7: IEEE802.15.4 superframe structure.

two successive beacon packets, as shown in Fig. 5.7. Each superframe is organized into two parts: the active part and the inactive part. The former is in turn composed of 16 slots of equal duration and organized into two parts: the Contention Access Period (CAP), during which channel access is ruled by CSMA/CA, and the Contention Free Period (CFP), where at most seven Guaranteed Time Slots (GTS) are allocated to packets of fixed size, according to a controlled access procedure. The durations of the active part and of the whole superframe, respectively Superframe Duration (SD) and Beacon Interval (BI) in Fig. 5.7, are determined by the values of two parameters, namely the Superframe Order (SO) and the Beacon Order (BO), which are integer numbers in the range 0-14. The expressions which determine the duration of the active part SD and of the superframe BI are the following:

$$SD = 16 \cdot 60 \cdot 2^{SO} \cdot T_S, \tag{5.2.1}$$

$$BI = 16 \cdot 60 \cdot 2^{BO} \cdot T_S, \tag{5.2.2}$$

where 16 is the number of slots, T_S is the duration of one symbol and $60 \cdot 2^{BO} \cdot T_S$ represents the slot duration T_{slot}. The back-off algorithm used here is the one reported in Section III of [152].

As a final remark, it should be clarified that, in the link between each IEEE802.15.4 node and its relevant coordinator affected by very small pathloss, losses occur only due to CSMA/CA, whereas channel fluctuations do not impact on them. Therefore, losses happen only in the CAP part of the superframe, since CFP guarantees contention-free access to nodes allocated on them.

For traffic originated in IEEE802.15.4 devices, the final Packet Loss Rate (PLR) is evaluated by taking into account both the losses due to CSMA/CA in the link between IEEE802.15.4 nodes and the relevant coordinators, and the losses due to channel fluctuations in the link between coordinators and sink.

5.2.3 Centralized Cross-Layer Scheduler over a Hierarchical Heterogeneous Ad Hoc Network

For the selection of the node to be scheduled, the cross-layer strategy proposed in Section 4.3 is used, and in particular the priority function in Eq. 4.3.1. However, due to the introduction of a new traffic model, it is worth rewriting it in order to highlight the redefinition of some parameters. In fact, the scheduler selects the node taking into account channel and time to deadline (T_D) of video and IEEE802.15.4 packets computed as:

$$T_D = \delta_{init} - T_{SQ}, \tag{5.2.3}$$

where δ_{init} is the playout delay in case of video application, or the maximum delay allowed in case of sensorial application, and T_{SQ} is the time spent in the radio link buffer in case of video traffic or:

$$T_{SQ} = T_{SQ,3} + T_{SQ,2}, \tag{5.2.4}$$

in case of IEEE802.15.4 traffic, where $T_{SQ,3}$ is the difference between the instant when a beacon packet is sent by the coordinator of the node under investigation and the instant when the packet is removed from the radio link buffer of the same IEEE802.15.4 node, and $T_{SQ,2}$ is the time spent in the radio link buffer of the coordinator.

Thus, the priority metric could be rewritten as:

$$P(T_D, CS) = \begin{cases} \kappa \cdot \exp(-\frac{(T_D - \tau)}{\varphi}), & T_D \geq \tau, \\ \kappa, & T_D < \tau, \end{cases} \tag{5.2.5}$$

where coefficients κ and φ depend on CS and on traffic class as for Eq. 4.3.1. Since this scheduling policy is slightly different from the CAA-E, since the former considers another mix of traffic leading to a different expression, from now on the proposed cross-layer scheduling policy including sensor data will be denoted as X-Lay. In Fig. 5.8, a graphical representation of the priority function in case of good channel state is reported depending on the different traffic classes and on different values of parameters τ and φ.

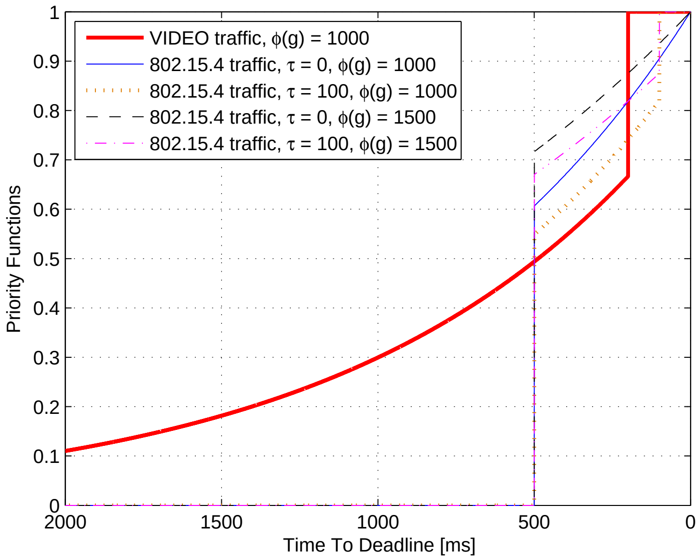

Figure 5.8: Graphical representation of the priority function for both video and IEEE802.15.4 traffic.

5.2.4 Numerical Results

$N = 10$ video terminals transmit pre-encoded VBR video streams. The buffer management strategy for video considers $N_{LB_v} = 60$ packets. $M = 9$ coordinators gather the traffic coming from $Z = 250$ IEEE802.15.4 nodes. SO and BO in Eqs. 5.2.1-5.2.2 are equal to 1, which means that there is no inactive period in the superframe, and T_S is equal to 16 μs, which leads to a superframe duration of 30.72 ms. IEEE802.15.4 packet size is equal to 200 bits and the number of GTSs is 7, thus, each coordinator guarantees transmission from 7 IEEE802.15.4 nodes toward the sink, whereas in case of more than 7 IEEE802.15.4 nodes connected to the coordinator, these should compete to access the channel through CSMA/CA. Finally, for IEEE802.15.4 traffic δ_{init} is 500 ms. This maximum delay is computed starting from the time instant when a coordinator sends the beacon packet used to synchronize the IEEE802.15.4 nodes

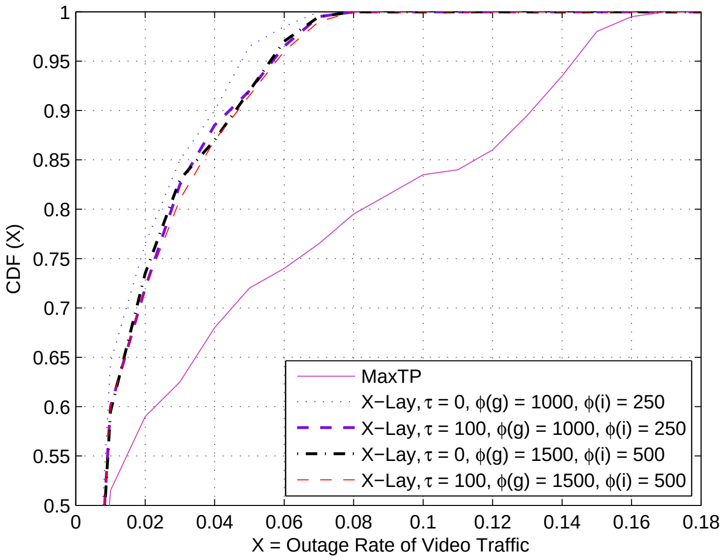

Figure 5.9: CDF of the outage rate for video terminals for X-Lay and MaxTP.

connected to it with respect to the superframe.

Scheduling parameters related to video traffic resulting from optimization performed in Section 5.1.3 are used. In particular, three possible channel states are considered taking into account that T_1 is equal to 0.8 and T_2 is 0.3. Then, in Eq. 5.2.5 κ is 1 in case of good and intermediate channel state, whereas it is 0 in case of bad CS, and φ is equal to 1000 in case of good channel state and 250 in case of intermediate channel state. τ is equal to 20 TTIs.

All scheduling parameters for IEEE802.15.4 traffic will be object of optimization in the simulation campaigns.

Scheduling Parameters Optimization for IEEE802.15.4 Traffic

In Fig. 5.9 performance of X-Lay compared to MaxTP are reported in case of video traffic. The CDF of the outage rate perceived by 10 video terminals is plotted for both strategies. In particular, for X-Lay the set of parameters used in Eq. 5.2.5 is the one reported above, whereas the parameters related to IEEE802.15.4 traffic are reported in the legend, with the exception of the buffer size, which is always set to 60 packets as for the video traffic. It can be noticed that X-Lay shows relevant improvements on system performance with respect to MaxTP, and with very small sensitivity to scheduling parameters for IEEE802.15.4 traffic. In fact, looking at outage rate equal to 0.05, the cross-layer scheduling gain is 20% with respect to MaxTP. This is due to the fact that RUs can be temporarily scarce due to channel fluctuations, hence, an application-suited strategy better manages the available resources among nodes. Moreover, X-Lay is robust with respect to parameter tuning, since the dominant factor in Eq. 5.2.5 is the exponential behavior, and not the specific set of parameters considered.

In Fig. 5.10, the CDF of the PLR in the link between coordinators and sink is reported for both scheduling strategies depending on the optimization of parameters τ, $\varphi(g)$ and $\varphi(i)$ for good and intermediate channel state in case of IEEE802.15.4 traffic in Eq. 5.2.5, when buffer size for IEEE802.15.4 traffic is equal to 60 packets. Similarly to Fig. 5.9, it can be noticed that MaxTP outperforms X-Lay in all cases, though performance is comparable, since only almost 5% of difference is between them. However, X-Lay is not sensitive to parameter tuning in Eq. 5.2.5, for the same reasons already explained in the comments on Fig. 5.9.

The Impact of MAC Protocols on IEEE802.15.4 Traffic

Concerning IEEE802.15.4 traffic, in Fig. 5.11, the CDF of PLR relevant to the traffic generated by IEEE802.15.4 nodes is reported for both scheduling strategies, with the

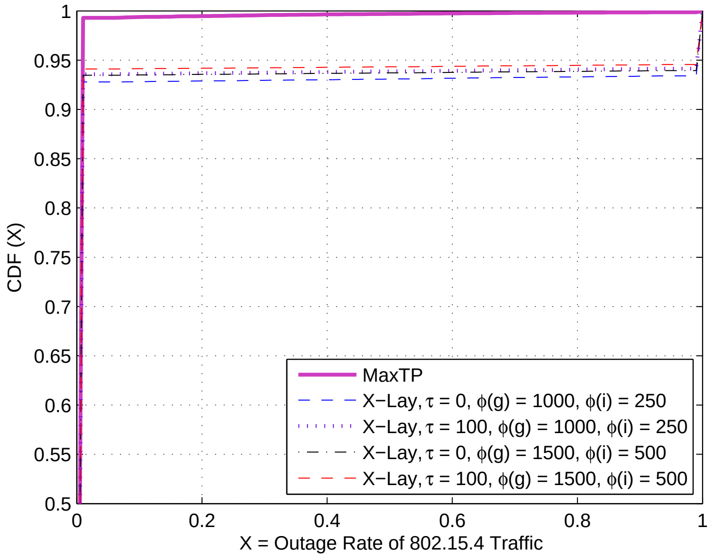

Figure 5.10: CDF of the PLR for IEEE802.15.4 traffic depending on scheduling parameters for X-Lay and MaxTP.

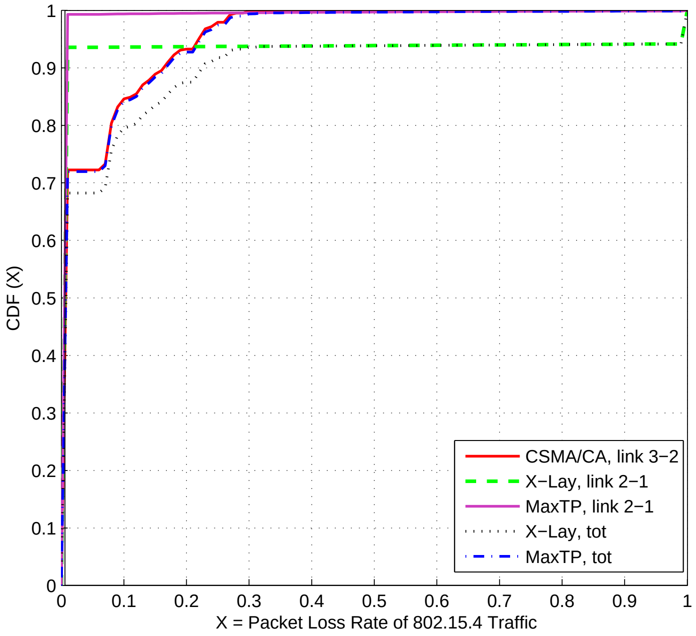

Figure 5.11: CDF of the PLR for IEEE802.15.4 traffic for X-Lay and MaxTP.

following set of parameters in case of IEEE802.15.4 traffic: $\tau = 100$, $\varphi = 1000$, $\varphi = 250$ respectively for the good and intermediate state, and $N_{LB_s} = 60$. In particular, the total PLR and the two possible causes of loss, *i.e.*, loss due to CSMA/CA in the link between level 3 (IEEE802.15.4) and level 2 (coordinators) nodes, and loss due to the wireless channel in the link between level 2 nodes and the sink, are highlighted. It can be noticed that most of the losses occur due to the CSMA/CA protocol, which in fact has more impact on the total PLR. Nevertheless, in this case MaxTP behaves slightly better than X-Lay. This is due to the fact that MaxTP allocates IEEE802.15.4 traffic as soon as it perceives better channel quality with respect to video traffic, and also to the fact that buffer size is too small. Hence, X-Lay, which mainly depends on T_D, can not satisfactory serve IEEE802.15.4 packets which are discarded even before their expiration.

In Fig. 5.12, a trace of the PLR of IEEE802.15.4 traffic is reported in case of X-Lay. The same set of parameters used for Fig. 5.11 is considered. In particular, the behavior of the PLR due to CSMA/CA, the wireless channel, and the total PLR over 100 frames in a certain scenario, are plotted. It can be noticed that a small number of packets is almost continuously lost due to packet collisions occurring in CSMA/CA. This means that, on average, more than seven IEEE802.15.4 devices are connected to a coordinator, so, there are no sufficient GTSs to serve level 3 devices in the contention-free period. The losses due to the wireless channel fluctuations occur less frequently, but a larger amount of packets is lost in a few frames, due to temporarily bad conditions, which last almost for the coherence time of the channel.

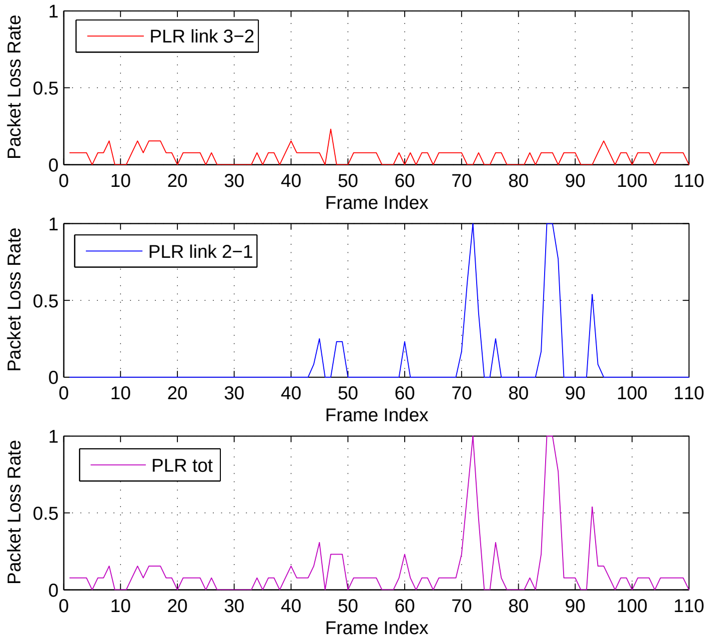

Figure 5.12: Traces of PLR affecting IEEE802.15.4 traffic.

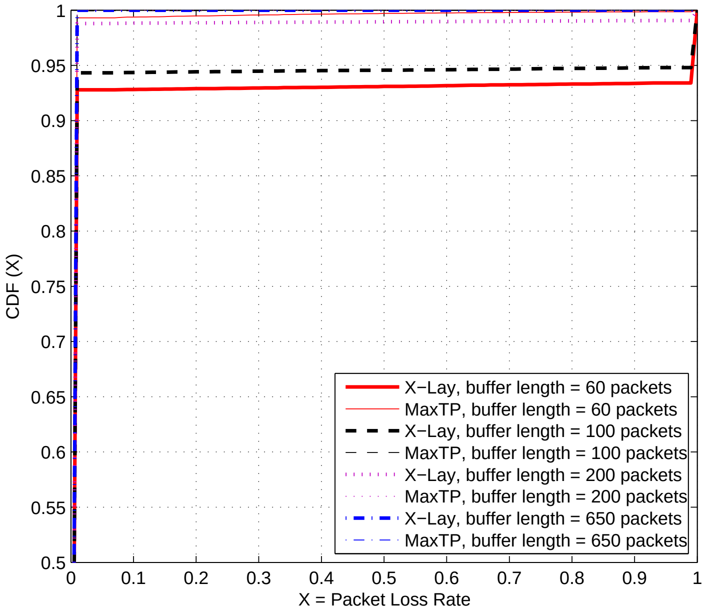

Figure 5.13: CDF of the PLR for IEEE802.15.4 traffic depending on buffer size for X-Lay and MaxTP.

The Impact of IEEE802.15.4 Traffic Buffer Size

In Fig. 5.13, the CDF of the PLR in the link between coordinators and sink is reported for both scheduling strategies depending on the optimization of the buffer size of IEEE802.15.4 traffic, given the following set of parameters in Eq. 5.2.5 for IEEE802.15.4 traffic: $\tau = 0$, $\varphi(g) = 1000$ and $\varphi(i) = 250$, respectively in the good and intermediate channel state. In this case, it can be noticed that the larger the buffer size, the smaller the advantage of MaxTP with respect to X-Lay: when the buffer size is equal to 650 packets, performance are similar in both cases. This picture shows that the most relevant cause of losses for X-Lay was the insufficient buffer size, which may not allow the device to store packets until their expiration time. The fact that a larger buffer size is requested in the case of IEEE802.15.4 traffic with respect to video may appear strange, since deadline constraints are stricter for video. However, this is due to the presence of the DDB strategy, which implements a smart selective packet removal not applicable in case of IEEE802.15.4 traffic.

Finally, in Fig. 5.14, the probability of having outage rate for video traffic and PLR for IEEE802.15.4 traffic smaller than 5% is reported as a function of the buffer size of IEEE802.15.4 nodes. The scheduling parameters of IEEE802.15.4 traffic are the same as reported above. This interesting result shows that there is a trade-off in the selection of this parameter, since the better the IEEE802.15.4 performance, the worse the video performance, as expected. However, the line for IEEE802.15.4 saturates at 200 packets.

From the results shown above, it is clear that in case of video traffic the proposed cross-layer scheduling strategy provides significant gains with respect to MaxTP, whereas, by optimizing the buffer size, the same performance are obtained by both

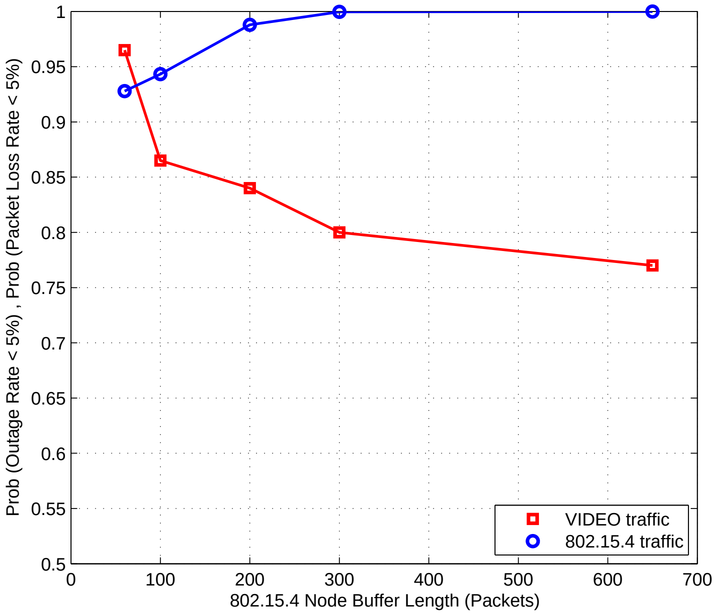

Figure 5.14: Probability of outage rate <5% for video traffic and of PLR <5% for IEEE802.15.4 traffic as a function of buffer size for IEEE802.15.4 traffic in X-Lay.

algorithms for IEEE802.15.4 traffic.

Chapter 6

Distributed Scheduling in an OFDMA Multi-Cell Network

In this Chapter a new method for distributed interference mitigation in full spectral-reuse OFDMA cellular networks is introduced. The method considers the use of predefined frequency-domain power profiles which help make interference more predictable across subcarriers. The interference mitigation gains are extracted thanks to a scheduler which examines the SINR experienced by users, based on the a priori known interference power profile. A method for optimizing the power profiles so as to guarantee fairness among users, given the a priori knowledge of the scheduling rule, is proposed. The advantage of this method over previously proposed approaches for interference mitigation based on power control is that in this case fully distributed scheduling can be performed, so that no exchange of signaling between the different cells is needed. In particular the use of a power control scheme, referred to as *power planning*, for OFDMA systems is proposed. This idea takes inspiration from the Partial Frequency Reuse (PFR) and Soft Frequency Reuse (SFR) concepts.

The PFR has been proposed for Global System for Mobile communication (GSM) [153], where the idea was that in each cell two areas were identified: an inner area where a unitary frequency reuse was applied, and an outer area where a higher frequency reuse was used at cell edge, *i.e.*, users in the outer area of a certain cell where allowed to transmit only on frequencies different with respect to the neighboring cells. This concept is depicted in Fig. 6.1.

A similar idea, the SFR, has been then elaborated to be applied to OFDM based systems like WiMAX and LTE, as recommended in [154], [155], [156], [157], [158], [159]. Also in SFR, the cell area is organized in an inner and an outer part, but users close to the cell center (or with high SINR) are allowed to transmit with a reduced power level possibly over the whole system bandwidth, whereas users close to the cell edge can transmit with high power in order to improve their data rate, but only on some parts of the system bandwidth, thus, outer areas of neighboring cells are assigned with different portions of the bandwidth. In this situation, cell center users can transmit on the bandwidth assigned to cell edge users even with high power, since this would not affect neighboring cells in downlink. However, since only a fraction of the entire frequency band can be used in the outer area, the peak rate of cell edge users is low and less frequency diversity is available when performing resource allocation.

The scheme proposed here is *dynamic in frequency domain* but *static in time domain*, in order to restore the predictability of interference. This aspect is essential so as to allow each cell to make a distributed scheduling decision, *i.e.*, independently on the actions taken in other cells. The power planning method works by identifying a power profile in the frequency domain and, contrarily to SFR, in presence

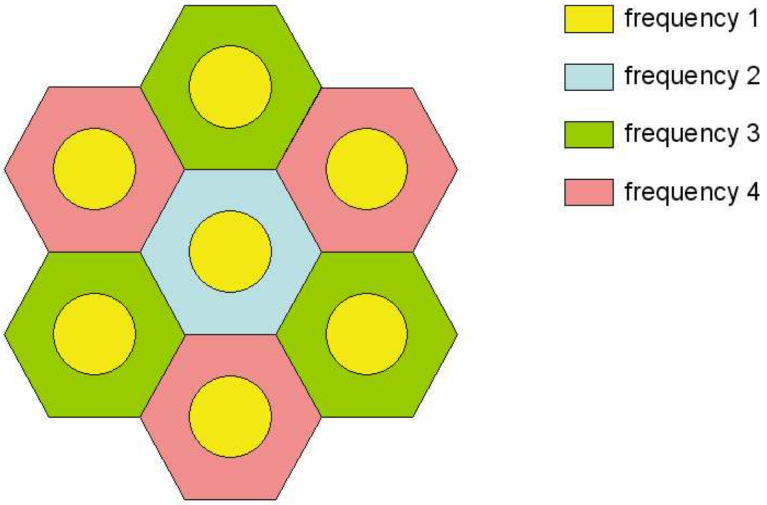

Figure 6.1: Partial frequency reuse concept.

of unitary spectral reuse over the whole system bandwidth. The power profile indicates the downlink transmit power associated in advance to each subcarrier. Then, each cell is assigned with a given power profile and all profiles are subject to a total power constraint over the subcarriers. A procedure to compute the power profiles is proposed. This procedure takes the form of an iterative off-line algorithm which optimizes iteratively the power planning vector and the scheduler, such that the obtained power planning vector is ideally matched to the desired scheduling rule. In particular, results about this power profile design method will be shown in case of distributed maximum throughput scheduling. Besides, a simple linear model for power profile definition is also proposed. In this case, a simple distributed scheduler aiming at guaranteeing fairness among users while taking into account channel conditions is introduced. This scheduler only requires a user to feedback the measured SINR to its serving base station only. The inter-cell coordination gains are achieved thanks to the interference-diversity effect, *i.e.*, for a given total interference I being measured, which neighboring bases contribute most to this interference at any given user is a random event, due to pathloss and fading effects. Strong and weak interfering sources are automatically assigned unequal transmit power levels, thanks to the scheduler.

Interestingly, other contributions exist in the literature suggesting the use of power profiles. For instance, [103] proposes the use of fixed unequal power levels over different time slots, in TDMA systems. The profiles are adjusted to as to create a soft frequency reuse pattern with strongly interfered slots and weakly interfered slots. However the powers and users are selected so that a prerequired SINR threshold is met. Furthermore, the calculation only considers one interfering base station per cell. More recently, a contribution to IEEE802.16 WiMAX [160] considers the use of power profiles for OFDMA. However, these profiles are dynamic and evolve on the fly taking into account users with new random channels. As a result, the interference pattern is not predictable and intercell feedback and signaling must be implemented to track the interference across cells.

6.1 Scenario

In this Chapter a wireless network is considered where a fixed number of cells N are deployed according to a hexagonal pattern. Each cell is equipped with an OFDMA transmission system composed of S subcarriers assumed to be used only in downlink, with omnidirectional antennas at each BS. Over the network area, a fixed number of users U are randomly and uniformly distributed. So, given the access technology, up to S different users can be served in each cell. The system exploits full reuse of spectrum in all cells.

Now let u_n be the index of a user connected to cell n, where n is the closest cell. User u_n is affected by long term pathloss depending on the distance from each cell m in the network according to the widely used expression:

$$L_{u_n}(m)(dB) = k_0 + k_1 \ln d(u_n, m) + sh_{u_n}(m), \tag{6.1.1}$$

where k_0 and k_1 are constants depending on the propagation environment, $d(u_n, m)$ is the distance between user u_n and cell m, and $sh_{u_m}(n)$ is the log-normal shadowing contribution. Moreover, short term Rayleigh frequency-selective fast fading coefficients $\gamma_{u_n}(m, s)$ are considered, where s is the subcarrier index. From now on, $ch_{u_n}(m, s)$, which is the contribution of both the long term and short term gains, will be denoted as “channel gain”, *i.e.*:

$$ch_{u_n}(m, s)(dB) = \gamma_{u_n}(m, s)(dB) - L_{u_n}(m)(dB). \tag{6.1.2}$$

In such system, the problem of resource allocation is addressed which, given the multiple access technology, consists in power and frequency allocation, and user scheduling. In particular, the aim is guaranteeing fairness among users, and evaluations are performed in terms of multi-cell capacity C_{net}, defined as:

$$C_{net} = \sum_{n=1}^{N} \sum_{s=1}^{S} C(s_n) = \sum_{n=1}^{N} \sum_{s=1}^{S} \log_2(1 + SINR_{\hat{u}}(s_n)), \tag{6.1.3}$$

where $SINR_{\hat{u}}(s_n)$ is the SINR experienced by the scheduled user $\hat{u}$, if any, allocated over subcarrier s of cell n. This is computed as:

$$SINR_{\hat{u}}(s_n) = \frac{P_{r,\hat{u}}(s_n)}{P_{noise} + I_{\hat{u}}(s_n)}, \tag{6.1.4}$$

where $P_{r,\hat{u}}(s_n)$ is the power received by user $\hat{u}$ allocated in cell n over subcarrier s, P_{noise} is the Additive White Gaussian Noise (AWGN) contribution, equal over all subcarriers, and $I_{\hat{u}}(s_n)$ is the interference power experienced by the same user:

$$I_{\hat{u}}(s_n) = \sum_{m=1, m \neq n}^{N} I_{\hat{u},m}(s_n), \tag{6.1.5}$$

where $I_{\hat{u},m}(s_n)$ is the power experienced by user $\hat{u}$ due to the transmission of cell m over the same subcarrier s. In such scenario, intercell interference is of primary concern, whereas intracell interference can be considered as negligible thanks to resource orthogonality.

Due to the multi-cell environment, in order to perform optimal scheduling and resource allocation, decisions should be taken in a centralized way at some control unit able to collect information from all users, and decide accordingly. However, as the number of cells grow, the complexity of these operations becomes prohibitive. So, a fully distributed approach is recommendable to keep complexity under control.

Thus, the aim is designing a completely distributed scheduling and resource allocation strategy among cells, with the objective of preserving fairness among users. In order to have a completely distributed strategy and make the interference level predictable, a novel power planning approach is proposed, which inserts some structuring in power allocation, as shown in the next Section.

As a final remark, the following assumption is performed: when taking decisions, each BS knows all useful and cross-link channel gains, from now on denoted as gain matrix, which is reasonable if a sufficiently long coherence time and the use of a feedback channel is assumed.

6.2 Multi-Cell Capacity with Power Planning

6.2.1 Concept Description

As already mentioned, the objective in this Chapter is to design a fully distributed resource allocation and user scheduling strategy over a multi-cell OFDMA network, whose aim is guaranteeing fairness among users, while evaluating the multi-cell capacity as defined in Eq. 6.1.3. To reach this goal, the selection of the user to be scheduled and of the resources[1] to be assigned to him, should be performed taking into account channel gain and received interference power. If a fully distributed approach is pursued, each BS can only rely on local information provided via a feedback channel by its own users. So, structuring is inserted inside the system, in order to make the interference level inside the network predictable.

Though in principle power levels can continuously vary inside a predefined range, it is proposed that only a certain set of possible power levels are allocable, and these are distributed among cells and subcarriers according to a predefined pattern. This concept is denoted as "power planning".

The network is organized in groups of K adjacent cells according to a regular pattern as done for frequency planning[2] and, for analogy, this group of cells is denoted as "cluster" and K as "cluster size". Then, the S equally spaced OFDMA subcarriers assigned to each cell are arranged in K groups of S/K adjacent subcarriers, from now on denoted also as "GoFs", as for the MC-CDMA case seen in previous Chapters,

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[1] From now on it will be defined as resource the couple subcarrier/transmit power level.

[2] Cells are arranged in group of K with $K = i^2 + i \cdot j + j^2$ and i, j integer numbers.

but without considering the CDMA dimension. It is clear that the larger the value of K, the smaller the frequency diversity if correlation between subcarriers is taken into account.

Having introduced the geometry of the system and the organization of the OFDMA spectrum, it is possible to move to the core idea of power planning, whose formalization is provided in the following.

6.2.2 Capacity Calculation

A vector power $\mathbf{P} = \left[P^{(1)} \cdots P^{(K)}\right]$ composed of K power levels is defined and denoted as "power profile". In the allocation process only these K power values are usable. From now on, this vector will be also named "multi-cell transmit power vector". At this stage, it is worth noting that K represents the cluster size, the multi-cell transmit power vector size and the number of GoFs composing the bandwidth of the system.

In each cell, each GoF is assigned with one of the values belonging to power vector $\mathbf{P}$, and over all GoFs inside a cell all values of $\mathbf{P}$ are exploited. Looking at a specific GoF, the set of cells belonging to the same cluster use all power levels available in $\mathbf{P}$ as well.

So, each cell in the network is assigned with a tag j ranging from 1 to K denoting the cell type. Then, since each tag is related to a specific power vector, *i.e.*, to a specific order of the possible K power levels in vector $\mathbf{P}$, cells with the same tag will be assigned with the same power vector, whereas cells belonging to the same cluster are assigned with permutations of the original power vector. For sake of clarity, the concept of power planning is graphically depicted in Fig. 6.2 for $K = 3$, where "cell type" denotes the tag assigned to a certain cell belonging to the cluster represented.

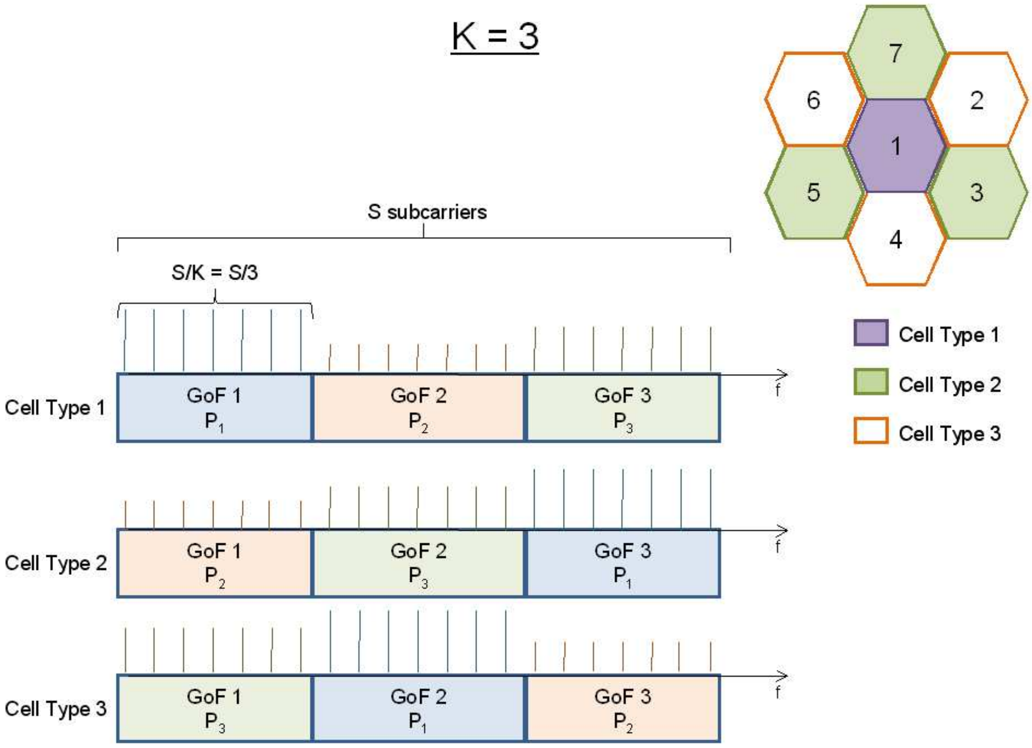

Figure 6.2: Power planning concept.

Finally, the multi-cell transmit power vector is subject to the following constraint on the average value:

$$\frac{1}{K}\sum_{k=1}^{K} P^{(k)} = \overline{P}. \tag{6.2.1}$$

Having inserted this structuring inside the system, it is possible to rewrite the capacity expression highlighting the contribution of the different types of cell:

$$C_{net} = \sum_{n=1}^{N} C_n = \sum_{j=1}^{K} \sum_{n^*=1}^{N_j} C_{n^*}^{(j)}, \tag{6.2.2}$$

where C_n is the capacity of cell n, N_j is the number of cells with tag j, $C_{n^*}^{(j)}$ is the capacity of the n^*-th cell of type j. For sake of brevity, in the following the analysis of the capacity in a target cell in case of cluster size K equal to 3 is reported, though everything holds for any possible value of K, and only the case of target cell of type 1 is considered. Moreover, only the first tier of interferers is taken into account, since this is the most relevant contribution to interference. Removing the cell index, the target cell of type 1 experiences a capacity $C^{(1)}$ equal to:

$$C^{(1)} = \sum_{g=1}^{K} \sum_{s^\star=1}^{S/K} C_{\hat{u}}^{(1)}(s_g^\star), \tag{6.2.3}$$

where $C_{\hat{u}}^{(1)}(s_g^\star)$ is the capacity perceived by user $\hat{u}$ allocated over the $s^\star$-th subcarrier of GoF g, which in turn can be computed as:

$$C_{\hat{u}}^{(1)}(s_g^\star) = \log_2(1 + SINR_{\hat{u}}^{(1)}(s_g^\star)), \tag{6.2.4}$$

where $SINR_{\hat{u}}^{(1)}(s_g^\star)$ is the relevant SINR. So, it is clear that three possible SINR expressions for target cell 1 can be computed, one for each GoF. According to the cell numeration in Fig. 6.2, in case of GoF 1 the SINR over a generic subcarrier $s_1^\star$ is:

$$SINR_{\hat{u}}^{(1)}(s_1^\star) = \frac{P^{(1)} ch_{\hat{u}}(1, s_1^\star)}{P_{noise} + I_{\hat{u}}^{(1)}(s_1^\star)}, \tag{6.2.5}$$

where $I_{\hat{u}}^{(1)}(s_1^\star)$ is the interference power experienced by user $\hat{u}$ allocated over subcarrier $s^\star$ of GoF 1:

$$I_{\hat{u}}^{(1)}(s_1^\star) = P^{(2)} \widehat{ch}_{2,\hat{u}}(s_1^\star) + P^{(3)} \widehat{ch}_{3,\hat{u}}(s_1^\star), \tag{6.2.6}$$

where:

$$\widehat{ch}_{2,\hat{u}}(s_1^\star) = ch_{\hat{u}}(2, s_1^\star) + ch_{\hat{u}}(4, s_1^\star) + ch_{\hat{u}}(6, s_1^\star) \tag{6.2.7}$$

and

$$\widehat{ch}_{3,\hat{u}}(s_1^\star) = ch_{\hat{u}}(3, s_1^\star) + ch_{\hat{u}}(5, s_1^\star) + ch_{\hat{u}}(7, s_1^\star). \tag{6.2.8}$$

The same analysis can be conducted for any type of target cell by properly permuting the power index.

The scheduling functionality can take advantage of the knowledge of the power vector when taking decisions about which users should be served and over which resources, since only the local gain matrix is required.

6.2.3 Scheduling Algorithms

In order to perform evaluations of the power planning strategy proposed, two scheduling strategies will be considered. The former is the well known opportunistic scheduler already described in Section 3.6.1, the latter is a simple original fairness-oriented strategy. However it is worth specifying that the analysis above holds for any kind of schedulers.

Opportunistic Scheduling Algorithm

As already described in Section 3.6.1, in each cell this policy selects for each subcarrier the user experiencing the maximum SINR:

$$\hat{u} = arg \max_{1 \leq u_m \leq U_m} SINR_{u_m}(s_m), \tag{6.2.9}$$

where U_m is the number of users connected to cell m, and $SINR_{u_m}(s_m)$ depends on the power profile. This strategy is run in each cell autonomously, hence, in a completely distributed way. In fact, having set the power values associated to each GoF in each cell during the planning stage, the amount of power coming from neighboring cells is known. Hence, only the gain matrix of its own users is required, which can be assumed to be known through the use of a feedback channel. Considering Eq. 6.1.4 and 6.2.6, it is clear that the selection of the users depends on the specific set of powers available and their association to GoFs.

Simple Fairness-Oriented Scheduling Algorithm

In each cell, this policy tries to allocate to each user the same target bit rate R_b^*. This is done by taking into account channel conditions experienced by each user. In particular, in each cell the allocation process starts always by the GoF assigned with the lower value of the power vector. Then, on each subcarrier the user with the highest SINR, given the relevant transmit power value, is selected. In fact, having set the power value associated to each GoF in each cell during the planning stage, also in this case the amount of power coming from neighboring cells is known. This process is repeated for each subcarrier, considering that as soon as a user reaches (or possibly overcomes) the target bit rate R_b^*, he is removed from the set of users to be served. Also this strategy is run in each cell autonomously, hence, in a completely distributed way, where only the gain matrix of its own users is required, which can be assumed to be known through the use of a feedback channel. Clearly, also for this strategy the selection of the users depends on the specific set of powers available and their association to GoFs.

In order to evaluate the performance provided by power planning, in the following Section two possible models to obtain power values are considered, namely the linear model and an iterative procedure.

6.3 Computing the Power Planning Vector

Having described the power planning concept, and provided the constraint set in Eq. 6.2.1, an open issue is how to suitably design the multi-cell transmit power vector. Here two possible models are presented: a simple linear model and an iterative power planning procedure making use of an alternate optimization of power and scheduling. Because the power planning vector is used in a static manner, these algorithms can be run off-line.

6.3.1 Linear Model

The K power values inside the multi-cell transmit power vector $\mathbf{P}$ lay on a straight line forming an angle ϑ with the line of the average power value $\overline{P}$. ϑ is restricted to the range 0 to $\pi/4$ since larger values will lead to the same set of power vectors read in the opposite direction.

Parameter ϑ defines the difference between the power levels inside the vector: *i.e.*, in case ϑ is equal to $\pi/4$ the maximum allowed difference between power values is obtained, whereas the case of ϑ equal to 0 leads to equal power values over all GoFs. All other values of ϑ lead to intermediate situations.

For sake of clarity, a graphical representation of the power values obtainable through the linear model is reported in Fig. 6.3 for $K = 3$. The optimization of

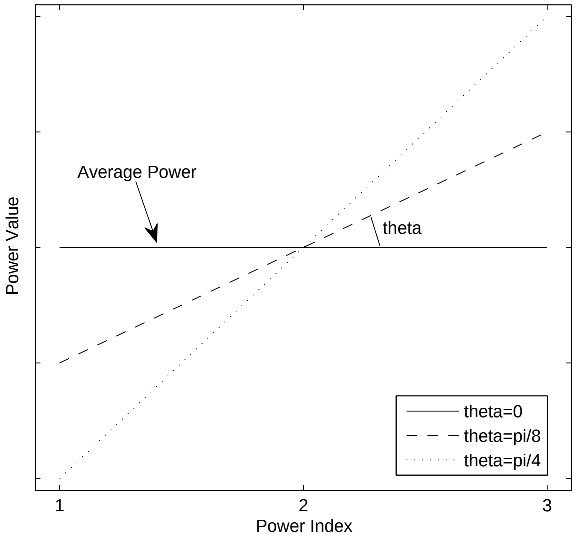

Figure 6.3: Liner power planning with $K = 3$.

the angle parameter is done via discretization and bruteforce search.

6.3.2 Iterative Procedure

Clearly, there are many possible ways to compute the multi-cell transmit power vector. Beside the linear model, whose drawbacks have been highlighted above, an iterative strategy has been also implemented.

In particular, an iterative is proposed whose objective is maximizing the overall network capacity C_{net}. This, as emphasized in Section 6.2.2, depends on the power vector, the power constraint set in Eq. 6.2.1, and the scheduling algorithm. From now on, the focus of analysis is on the case $K = 3$, though it is easily extendible to any possible value of K.

Due to the wireless environment, finding a power vector which is "optimum" for any system configuration is infeasible. In fact, by changing user positions and channel realizations, different values of interference are suffered and, hence, different transmit power values could be most suitable. However, since the objective is performing power planning, *i.e.*, fixing power values and using them during at least a long term time horizon, here it has been chosen to find the power levels which maximize the overall network capacity given a specific scenario, *i.e.*, a set of user positions and channel realizations, and then to compute the average power vector over a high number of scenarios in order to average the impact of random variables.

In order to reduce complexity with respect to an exhaustive search procedure, a finite set composed of a large number of different scenarios N_s, such that it could be approximated as infinite, is considered. Each scenario is characterized by different positions and channel realizations. Then, the values of the power vector are computed through the use of the gradient-ascent method aiming at maximizing the network capacity. In particular, it acts as follows:

1. a certain power vector is fixed;
2. a set of U users is uniformly and randomly deployed over the area under investigation, with the relevant gain matrix, including the cross-link gains;
3. users are scheduled according to the scheduling strategy under consideration;
4. network capacity is computed for the particular scenario according to Eq. 6.1.3;
5. the power vector is updated according to the gradient-ascent of capacity;
6. algorithm goes back to step 2 until N_s scenario statistics have been gathered;

then, the procedure computes the average over the N_s power vectors obtained, one for each scenario. In Fig. 6.4 the convergence of the power vector components in case

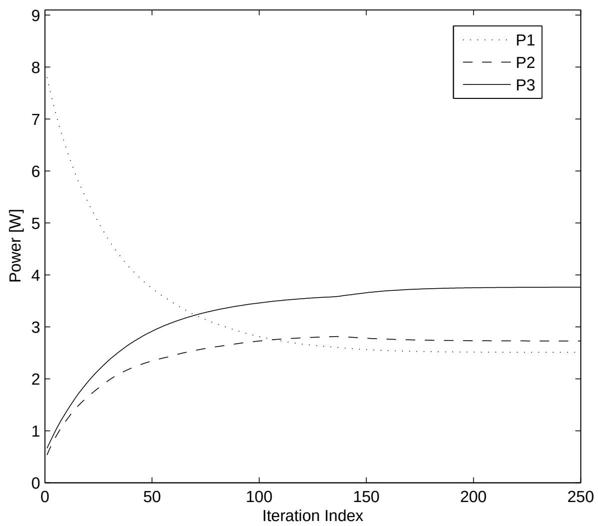

Figure 6.4: Convergence of the components of the power vector in case $K = 3$.

of $K = 3$ is plotted for a randomly chosen scenario.

It is worth noting that one of the major advantages of this approach is that it computes the power vector by including the scheduling algorithm implemented in the network. Nevertheless, the same procedure can be applied to any kind of scheduler just including the scheduling strategy of interest in the iterative procedure.

6.4 Simulations

The power planning strategies proposed are compared with the case where all cells and subcarriers are assigned with equal power levels. Performance are evaluated for cluster size K equal to 3, though the analysis above holds for any cluster size value.

In order to test the behavior of the strategies proposed, no specific realistic systems are considered. Results are obtained via simulation considering a network composed of N equal to 9 cells, each one with S equal to 128 subcarriers available for allocation, and interfered by the 6 closest cells, *i.e.*, the first tier of interferers, since higher orders of interferers are negligible. The number of users inside the network U is equal to 288. The other parameters are: k_0 equal to 40 dB, k_1 equal to 15.2, the shadowing variance is 8 dB, $\overline{P}$ is set to 3 Watts and the total bandwidth is 3.84 MHz. As a performance metric the CDF of the capacity computed over each subcarrier of each cell for 10 scenarios is considered, since this number has been proved to be sufficient to make evaluations.

In Fig. 6.5 the CDF of the network capacity is reported in case of opportunistic scheduling. In the plot "EP" refers to the case of equal power assigned to each GoF over each cell, "LM" refers to the linear model for which different values of ϑ are evaluated, and "IP" refers to the iterative procedure, which is implemented by taking into account $N_s = 100$ different realizations. The figure shows that power planning does not give any advantage in terms of outage capacity in case of maximum sum rate scheduling, but at most shows the same performance of the equal power case (for $\vartheta = \pi/8$). However, a small gain is given in terms of average capacity. This is due to the scheduling algorithm which, trying to pursue maximum capacity over the network, selects the best users, *i.e.*, the closest ones to the base station. Since these users suffer from very low interference, power planning does not give any substantial benefits.

From now on, the iterative procedure and the opportunistic scheduling technique will not be considered anymore, since for sake of time the inclusion of the fairness-oriented strategy in this procedure has not been performed, and the power planning has been proven to be not beneficial in case of opportunistic scheduling. So, the focus will be only on the linear model in comparison with the equal power case for

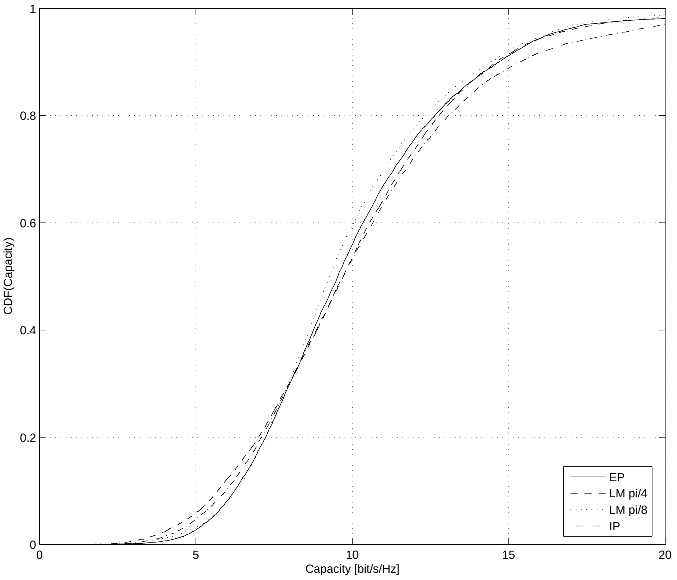

Figure 6.5: CDF of the capacity in case of opportunistic scheduling.

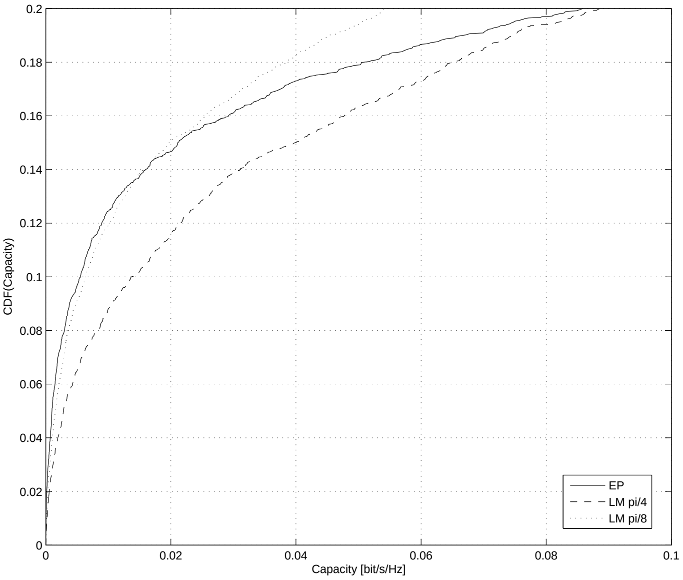

Figure 6.6: CDF of the capacity in case of target rate equal $R_b^* = 3$ kbit/s.

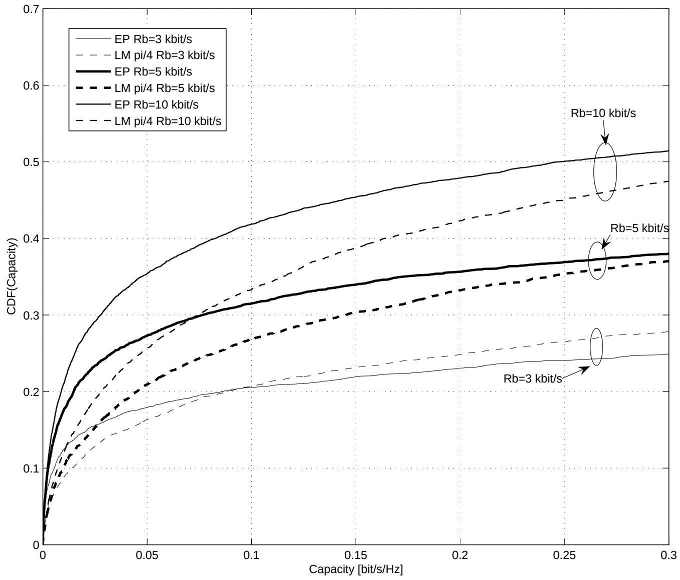

Figure 6.7: CDF of the capacity depending on target rate R_b^*.

the fairness-oriented scheduling. In Fig. 6.6 the CDF of the network capacity is reported in case $R_b^* = 3$ kbit/s. Though this value is lower with respect to typical data rates, this has been chosen just to have a hint of the behavior of the strategy proposed. In fact, also other R_b^* values have been taken into account in numerical evaluations. The figure shows that the linear model significantly outperforms the equal power assignment among cells at least for $\vartheta = \pi/4$. This happens because power planning allows the scheduler to better exploit the multiuser diversity, while mitigating interference through the use of lower power levels when possible and higher when needed.

In Fig. 6.7 the outage network capacity in case of fairness-oriented scheduler depending on target rate R_b^* is reported. This Figure shows there is always at least one linear power vector outperforming the equal power case for all R_b^* values reported.

Nevertheless, the more demanding the system is (*i.e.*, $R_b^* = 10$ kbit/s), the higher the outage capacity, as expectable.

Chapter 7

Discussion and Open Issues

In this Thesis radio resource allocation over multi-carrier based wireless systems has been investigated. The analysis involved different kinds of multi-carrier air interfaces, like OFDMA and MC-CDMA, different network architectures, like single-cell, multi-cell, hierarchical opportunistic networks, and different approaches have been taken into account, like cross-layer, centralized and distributed.

In particular, as an original contribution with respect to the literature, in this work a numerical evaluation of the advantage introduced by cross-layer resource allocation with respect to traditional layered approaches, has been performed in the presence of a complete channel model and realistic traffic traces. Results have shown that in a single-cell, or in a multi-cell scenario where decisions are taken at each base station, the exploitation at the scheduler (laying at the MAC layer) of information coming from non-adjacent layers, and in particular from the application layer, and the channel state information, provides significant benefits in terms of QoS for users, thus allowing a better usage of radio resources, with respect to traditional scheduling policies.

As a secondary original result, the cross-layer centralized approach proposed for the cellular scenario, has been extended in order to be applied to a different kind of network. In particular, an innovative emergency-deployed network organized in a hierarchical structure and based on the paradigm of opportunistic networks has been proposed, where still a multi-carrier air interface is considered. Results show how even in presence of a completely different network, composed of a heterogeneous mix of traffics characterized by different application requirements, the cross-layer approach brings substantial benefits with respect to traditional scheduling policies.

Then, the focus has been shifted towards distributed approaches to resource allocation in multi-cell multi-carrier based networks. In this case, the main objective was to manage the interference generated and suffered by each cell in the scenario, making it predictable by fixing the power levels assigned to each of the subcarriers available in the system. The introduction of this structuring, though reducing the number of degrees of freedom inside the system, is beneficial in order to allow a fully distributed and reduced complexity implementation of radio resource allocation algorithms among cells.

Even if the entire work has been conducted without any specific reference to emerging 4G standards (like WiMAX, LTE), the results achieved can be applied to such systems.

Despite the extensive analysis performed on the topic of radio resource allocation, some issues are still open and leave room for future investigations. In particular, it could be of great interest integrating the cross-layer approach studied for MC-CDMA systems in presence of realistic traffic types, with the structuring in power allocation proposed for the OFDMA multi-cell network.

In fact, though some years ago the MC-CDMA attracted a strong interest in research community thanks to the availability of many degrees of freedom resulting from the combination of OFDMA, TDMA, and CDMA, this interest in the end moved towards simpler OFDMA systems, which are already able to cope with frequency selectivity and time variance without the increased complexity introduced by the code dimension.

Moreover, modern and future broadband wireless systems in many cases exploit unitary frequency reuse. This is due to the fact that the spectrum resource is scarce and expensive, thus, it should be used as efficiently as possible. However, in such conditions, interference is a primary concern. Thus, it can be imagined that introducing the power planning concept in a realistic network, able to make interference predictable in the system, in combination with cross-layer scheduling policies, able to efficiently manage different classes of traffic, could be really beneficial both for users' satisfaction and operators' revenue.

This merge would allow a completely distributed implementation of scheduling and radio resource allocation at each cell independently on the others belonging to the network. In fact, it could be imagined that, thanks to some local measurements performed by the mobile devices in case of downlink (to be reported to the base station) or by the base station itself in uplink, each cell could be able to predict the interference level perceived over each subcarrier, thanks to the power structuring. Hence, when taking scheduling and radio resource allocation decision, the base station can exploit this prediction, and include this procedure in a more complex scheduling policy based on cross-layer approaches, in order to fit the decision to the specific application under consideration.

This implementation would be really fully distributed, since no signalling exchange is requested between base stations. Hence, the increased complexity due to cross-layer, would be compensated by the reduced complexity (at least in the multi-cell dimension) allowed by the no need of signalling among cells.

This approach, though proposed and investigated in case of cellular networks, can be even matched to the case of ad hoc networks. In fact, the distributed implementation and the absence of signalling among nodes perfectly fit with the paradigm and characteristics of ad hoc networks, according to which each node most probably takes decisions autonomously with respect to others in resource allocation. Also in this case the inclusion of cross-layer scheduling strategies can be foreseen, possibly in combination with other functionalities like, *e.g.*, routing.

The implementation of controlled access schemes to the wireless medium over decentralized network architectures, is still a totally open issue. Hence, the design of such strategies by considering also multi-carrier systems is a hot topic which leaves room for extensive future investigations.

Chapter 8

Acronyms

2G 2nd Generation

3G 3rd Generation

3GPP 3G Partnership Project

4G 4th Generation

AAA Authentication Authorization and Accounting

AC Admission Control

AMC Adaptive Modulation and Coding

AP Access Point

ARA Adaptive Resource Allocation

AVC Advanced Video Coding

AWGN Additive White Gaussian Noise

BCH Bose-Chaudhuri-Hoequenghem

BER Bit Error Rate

BI Beacon Interval

BO Beacon Order

BS Base Station

BSC Base Station Controller

BW Bandwidth

C/I Carrier-to-Interference

CAA Channel- and Application-Aware

CAA-E Channel- and Application-Aware with Exponential Function

CAP Contention Access Period

CDF Cumulative Distribution Function

CDMA Code Division Multiple Access

CFP Contention Free Period

CIF − Q Channel condition Independent Fair Queuing

CPU Central Processing Unit

CRRM Common Radio Resource Management

CS Channel State

CSI Channel State Information

CSMA Carrier Sensing Multiple Access

CSMA/CA Carrier Sensing Multiple Access with Collision Avoidance

DDB Drop Dependency Based

DFT Discrete Fourier Transform

DSP Digital Signal Processing

EDF Earliest Deadline First

FDM Frequency Division Multiplexing

FEC Forward Error Correction

FTP File Transfer Protocol

GERAN GSM/EDGE Radio Access Network

GoF Group Of Frequencies

GoP Group of Pictures

GPS Generalized Processor Sharing

GSM Global System for Mobile communication

GTS Guaranteed Time Slots

HLR Home Location Register

HO Handover

HOL Head-Of-Line

HSDPA High Speed Downlink Packet Access

HSPA High Speed Packet Access

IBS Infinite Buffer Size

ICI Intercarrier Interference

IDFT Inverse Discrete Fourier Transform

IP Internet Protocol

ISI Intersymbol Interference

ISO/OSI International Standard Organization/Open System Interconnection

IWFQ Idealized Wireless Fair Queuing

LA Link Adaptation

LAN Local Area Networks

LP Linear Programming

LTE Long Term Evolution

MAC Medium Access Control

MaxTP Maximum Throughput

MC Multi-Carrier

MC-CDMA Multi Carrier-Code Division Multiple Access

MIMO Multiple Input Multiple Output

MRC Maximal Ratio Combining

MSR Maximum Sum Rate

NEWCOM Network of Excellence in Wireless Communications

NLOS Non-Line-Of-Sight

NoE Network of Excellence

NP Nondeterministic Polynomial-time

NRT Non-Real Time

OFDM Orthogonal Frequency Division Multiplex

OFDMA Orthogonal Frequency Division Multiple Access

OS Opportunistic Scheduling

PAN Personal Area Network

PC Power Control

PDF Probability Distribution Function

PF Proportional Fair

PFR Partial Frequency Reuse

PHY Physical

PLR Packet Loss Rate

PRC	Proportional Rate Constraints
QCIF	Quarter Common Intermediate Format
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
RAN	Radio Access Network
RMS	Root Mean Square
RNC	Radio Network Controller
RR	Radio Resource
RRA	Random Resource Allocation
RRM	Radio Resource Management
RT	Real Time
RU	Resource Unit
SBFA	Server Based Fairness Approach
SD	Superframe Duration
SDMA	Space Division Multiple Access
SFB	Simple Finite Buffer size
SFR	Soft Frequency Reuse
SINR	Signal-to-Interference-plus-Noise–Ratio

SIR Signal-to-Interference Radio

SNR Signal-to-Noise–Ratio

SO Superframe Order

SoA State of the Art

SRA Simple Resource Allocation

TB Transport Blocks

TBLER Transport BLock Error Rate

TD Time-to-Deadline

TDMA Time Division Multiple Access

TS Type-of-Service

TTI Transmission Time Interval

UDD Unconstrained Delay Data

UMTS Universal Mobile Telecommunication System

UTRAN UMTS Terrestrial Radio Access Network

VBR Variable Bit-Rate

VHO Vertical Handover

WAF Wireless Adapted Fair

W-CDMA Wideband-Code Division Multiple Access

WFS	Wireless Fair Service
WiMAX	Wireless interoperability for Microwave Access
WLAN	Wireless Local Area Network
X-Lay	Cross-Layer
Y-PSNR	Peak-Signal-to-Noise–Ratio

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