THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

POWER CONTROLLED RADIO RESOURCE MANAGEMENT FOR QOS AWARE AD-HOC COMMUNICATION PARADIGMS

by

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Introduction

Ad-hoc networking today represents an active field capturing wide interest in the research community. Although significant work has been devoted to this field for nearly 30 years, only the past few years have assisted at a very explosion of the network community's interest [1]. The motivations can be found in the key factors that are expected to drive the wireless networks' evolution in the coming years. Among these, the universal popularity of Internet and the wide-spread demand for always-on access to data could bring to design wireless networks similarly to today packet based networks and computing devices [2]. Besides Internet, the achieved success of the 2G cellular systems and the expected one of their evolutions (2.5G and 3G) are driving forces for a development of mobile wireless data communications towards wireless ad-hoc networking. In this scenario ad-hoc networking, though in its early stage of maturity, is a promising means to primarily extend portable access having the ability to adapt and exist without substantial infrastructure [3][4].

An *ad-hoc network* is a collection of mobile radio devices cooperating to establish ubiquitous communications without the aid of a central infrastructure. An intrinsic characteristic of such systems is that the network links are dynamic — i.e., likely to break and change as the nodes move. The ALOHA network, born with the objective of connecting educational facilities in Hawaii, can be considered the first example realizing the ad-hoc paradigm [5][6]. Its protocol supports distributed channel access in a single-hop network hence providing a basis for the subsequent development of distributed channel access schemes that are suitable for ad-hoc networks. The second major example is represented by the project DARPA which worked on a multi-hop network, the Packet Radio network [7]. These first experimental packet radio networks as well as the ones later developed never take off in the consumer segment. So far, this network model has been considered just for military applications thanks to its operative advantage (or even necessity) of a decentralized configuration lacking of an infrastructure while, as for the commercial sector, equipments for wireless computing have not been available at an attractive price. Today enabling factors of ad-hoc networking seem to be the advancement of wireless data communication in terms of technology and penetration and license-free frequency bands, which could encourage the adoption of radio technologies (such as Bluetooth [8] and 802.11 [33]) allowing inexpensive and effortless deployment of wireless communication.

The landscape of possible applications of the ad-hoc communication paradigm is quite large. It could be adopted to cheaply extend the coverage area of fixed or cellular networks in urban areas. When no infrastructure is available, it could allow rescue operations or quick deployment of local coverage in remote sites. Ad-hoc networks could be employed as local networks (e.g., in a conference to link participants' notebooks among each other and to some local Internet server) or applied in the context of home networking. A further possible application scenario getting success nowadays is represented by sensor networks for environmental monitoring [10]. Finally, in the framework of small-scale personal area networks, the adoption of the wireless ad-hoc model would eliminate the need for cables interconnecting mobile devices such as cellular phones with the relevant accessories (headphones, etc.) and PDAs (Personal Digital Assistant). The most promising short-range technology for such application is Bluetooth.

Several technologies have been introduced in the recent past which enable ad-hoc mode of communication. For instance, besides the afore mentioned Bluetooth and IEEE 802.11 enabling fully decentralized radio access, also HIPERLAN/2 provides a direct mode of communication between terminals [11]. In spite of the discussed advantages of such technologies strictly related to the lack of an infrastructure, the dynamic nature of the links and the need of a distributed network management imply several challenges to the design and implementation of a packet radio architecture. Among these, a major issue concerning the *Radio Resource Control* (RRC) is the design of an access control strategy able to effectively manage interference from and toward competing technologies employing the same (license-free) frequency band by means of a suitable power management scheme. Other challenges are:

- the trade-off to pursue among delay requirements, network connectivity and capacity and power saving;
- the fluctuation of capacity and latency of links;
- the distributed operation mode of security and routing functions with the contemporary need of minimizing the required signaling overhead while ensuring connectivity.

As far as the physical layer is concerned, the two major technologies promising to achieve high data rates and considered for the 4G are Orthogonal Frequency Division Multiplexing (OFDM) [12] and Ultra Wide Band (UWB) radio [13][14]. Code Division Multiple Access (CDMA) [15] is very likely to be adopted as multiple access technique; for example, a CDMA version of OFDM consists in the Multi-Carrier CDMA while an UWB physical layer implements still a spread spectrum technique achieving low power spectral density. The major advantage of CDMA is due to the noise-like properties of the spread spectrum signal which implies that the co-channel interference behaves like additive white gaussian noise; this feature is mostly desirable when considering ad-hoc networks which lack of a cell planning and are likely to be based on technologies employing license-free frequency bands, such as the ISM (Industrial Scientific Medical) one. To allow uncoordinated networks to share the same frequency band, spread spectrum multiple access can be exploited resulting in noise-like interference that can be managed by a proper RRC strategy thus increasing the number supported users.

The focus of this thesis is on the topic of an access control scheme providing for power management. This research issue constitutes a significative example of the new design philosophy of wireless networks, which are evolving towards models violating the traditional layering methodology of OSI (Open System Interconnection) [16] according to a cross-layer integration in order to allow different parts of the protocol stack to adapt to the circumstance environment thanks to the information available at other layers [11]. The cross-layer network design aims at meeting the challenges of ubiquitous wireless access with differentiated QoS (Quality of Service) requirements by considering network functions together. Besides cross-layer design, cross-layer adaptability is required in order to dynamically match QoS requirements in changing conditions of network topology load, interference and radio channel. The proposed distributed RRC scheme is based on power regulation, where typical physical layers parameters (power, interference, etc.) are combined with upper layers ones to *i*) increase radio channel utilization; *ii*) perform admission control of heterogeneous wireless links; *iii*) maintain negotiated QoS levels expressed as a function of the Signal-to-Interference-Ratio (SIR). Power control is thus exploited as the paradigm to accommodate in the network users which are heterogeneous with reference to both QoS requirements (data rate, packet error rate, etc.) and perceived quality of the wireless link (radio channel, interference conditions, etc.) [17][18].

An innovative contribution of this work is to consider ad-hoc networking as a *communication paradigm* which can be flexibly and effectively applied to wireless networks with or without infrastructure. The common underlying philosophy adopted in both cases is represented by the distributed nature of the radio access scheme: according to the ad-hoc like model all RRC operations are performed autonomously by the network nodes without the aid of the infrastructure, even when this is actually present. In this framework, the contribution of this thesis is twofold:

- proposing a distributed admission control scheme based on power control aiming at providing an efficient and flexible radio resource sharing on one side and QoS support on the other side; the access scheme is defined within the general framework of a distributed radio access scheme adopting the ad-hoc networking model;

- applying this approach in the context of a wireless system employing UWB; as case study, an infrastructure architecture providing open radio access to the backbone is considered as proposed in the European IST project WHYLESS.COM [19].

The project WHYLESS.COM is studying the potentiality of the UWB technique for the development of an *Open Mobile Access Network* — i.e., an access network based on a versatile air interface providing an open platform to support QoS aware services through a network architecture which combines the UWB radio access procedures with a stateless IP QoS paradigm [20].

The thesis is organized according to the following structure. In Chapter 1 the state-of-the-art of ad-hoc networking is summarized with particular focus on open research issues concerning the radio access control. Chapter 2 is devoted to the specific topic of distributed power controlled resource management in wireless networks; the problem is studied in a general framework from the point of view of the employed access technology. In particular a survey of current solutions is provided and then a proposal is presented and described with reference to both the algorithm and the protocol aspects. Chapter 3 presents the application of the proposed RRC scheme to the UWB access system considered in the WHYLESS.COM project. The results obtained with the performance analysis are reported and discussed in Chapter 4. Finally the conclusions of this work are drawn.

Chapter 1

Ad-hoc networking and distributed access control

1.1 An introduction to ad-hoc networks

An ad-hoc network is a wireless system of nodes that dynamically self-organizes in arbitrary and temporary network topologies. As a result, the network nodes can be internetworked without the aid of a preexisting communication infrastructure. A possible additional feature of these networks concerns the capability of its radio nodes to relay other nodes' traffic thus giving rise to a multi-hop network; otherwise just single-hop (i.e., direct) communications are possible. A possible example of ad-hoc network is shown in Figure 1.1 representing a scenario of a business meeting where there take place a multi-hop connection of a mobile device towards a fixed station and a direct data exchange between a laptop and a PDA.

The typical operational characteristics of these radio systems affect the requirements for related networking function. Below the main properties of an ad-hoc network are listed [3].

Self-organization. Nodes can not rely on a network in the background to access the shared radio channel and to support security and routing functions. Instead they are required to autonomously discover the available radio resources and to perform security functions and routing in a distributed way, thus self-organizing in a connected network. The routing for

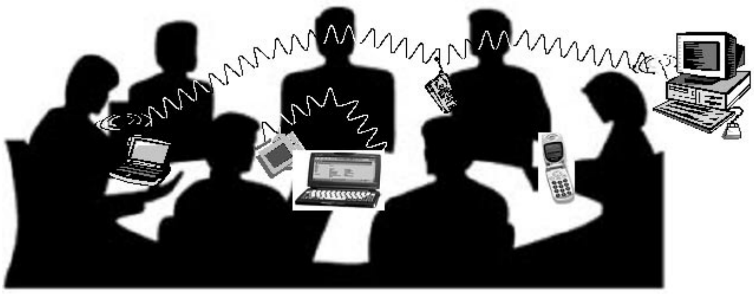

Figure 1.1: Example of ad-hoc network

ad-hoc networks has been widely studied and in literature several proposals can be found which face this issue in the framework of the QoS support [21].

Dynamic network topology. As radio nodes enter or leave the network — switching on or off — or move away, the topology will change randomly with time. Also this property call for self-configuration capabilities of radio nodes in order to adapt to the changed topology. Specifically, connectivity should be maintained; to this end, proper routing protocols must be designed allowing applications and services to operate not disrupted. In addition, mobility must be supported.

Distributed resource sharing. Functions related to access control and resource sharing must be performed autonomously by nodes according to a peer-to-peer communication model due to the lack of an entity acting as central controller. This issue results particularly challenging in the support of QoS, whose assurance requires also the introduction of admission control of entering communications.

Power/energy constraints. In general, radio nodes will be battery-driven as well as power limited. Moreover, since the technologies for ad-hoc networking will mostly operate in license-free frequency bands, also the interference produced in air must be kept under control. While the need of a tight power budget of the device will affect — for instance — CPU processing, memory usage, signal processing and transceiver output/input power, the interference control issue coupled to the limited power one call for a dynamic power

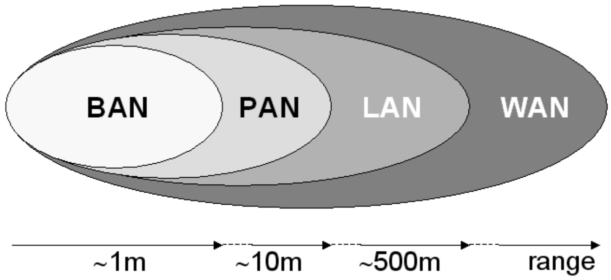

Figure 1.2: Taxonomy of ad-hoc networks [22]

management in order to adapt emission to the current interference conditions of the environment.

Ad-hoc networks can be classified depending on their coverage areas into four main classes: Body (BAN), Personal (PAN), Local (LAN) and Wide (WAN) Area Networks, as illustrated in Figure 1.2 [22]. Wide area ad-hoc networks have to be considered as mobile multi-hop wireless networks and thus present a number of challenges to be still solved, concerning for example routing and security; as a consequence they are not expected to be available for some time. On the contrary, wireless ad-hoc single-hop BANs, PANs and LANs, which are on smaller scales of the coverage area, are very likely to appear soon.

A BAN provides the connectivity among the components of a ”wearable computer” (e.g., earphones, microphones, etc.) which are distributed on the body; the communication range is $1 \div 2\ m$. The capability to interconnect with other BANs or PANs should be supported in order to exchange data with other people or access the Internet. A BAN is designed to interconnect heterogeneous devices — which may be complete devices such as cellular phones or components of a device (e.g., displays) — and with the capability of auto-reconfiguring as devices are added to or removed by the BAN.

A PAN involves mobile devices in the surrounding of the person enabling interconnection of a BAN with the environment around it and of the BANs of people close to each other with typical communicating range up to $10\ m$. These networks are mainly devoted to serve new applications arising from the possibility to build an ad-hoc network among the person’s workspace electronic devices. Moreover, PANs are expected to make possible pervasive applications (such as employing electronic tickets at airports with automatic selection of the seat).

A Wireless LAN (WLAN) is designed to provide wireless interconnection within a single building or a cluster of buildings, achieving a typical communication range of $100 \div 500\ m$. The implementation of a WLAN can be carried out according to two different approaches: an infrastructure based approach or an ad-hoc network one. In the first case, there exists an Access Point acting as centralized controller of the access to the air interface of the mobile stations and providing them also Internet access. On the contrary, according to the ad-hoc network approach peer-to-peer communications are established among stations without the aid of a fixed controller. As an alternative, a hybrid solution between the two could be possible where the communication paradigm would be still ad-hoc while there would be also Access Points providing only access to the Internet. The flexibility of this solution stands in the fact that all communications would be established in an ad-hoc fashion allowing the coexistence of local communications (i.e., communications between stations in radio visibility) with Internet connections. In the design of a WLAN, the typical requirements of a LAN, mainly consisting in high capacity and full connectivity, have to be met facing the specific problems of the wireless systems, that is bandwidth limitation, power consumption, mobility, security on the air.

1.2 Technologies for ad-hoc networking

Currently, the emerging standards for ad-hoc wireless networks are mostly represented by IEEE 802.11 ([33]) and Bluetooth ([8]). In addition, HIPERLAN/2 ([11]) should also be mentioned, although this technology employs as a rule a Centralized Mode where mobile terminals communicate through Access Points. The ad-hoc mode of operation of HIPERLAN/2 is the so-called Direct Mode allowing indeed direct communications among mobile terminals. However also in this mode the Access Point needs to control the radio access and thus two mobile terminals can communicate only having an Access Point within reach; as a consequence, HIPERLAN/2 does not provide for pure ad-hoc communications. As far as 802.11 and Bluetooth are concerned, the first standard constitutes a simple platform for implementing single-hop ad-hoc networks covering areas with extension of a WLAN while the second one (a *de facto* standard operating on the smaller scales of BANs and PANs) can build ad-hoc networks interconnecting devices on the person or around it within a radius of about $10\ m$. In the following the architecture and protocols of these two technologies are briefly described.

1.2.1 IEEE 802.11

The IEEE 802.11 standard for single-hop WLANs was introduced in 1997 permitting to achieve data-rates up to $2\ MBit/s$ [23]. In 1999 the task group 802.11b produced a standard for operating in the ISM $2.4\ GHz$ band with data rates up to $11\ Mbit/s$ [24]; the achievable rates was then further incremented — up to $54\ Mbit/s$ — by the 802.11a task group with the creation of a standard operating in the ISM $5\ GHz$ band. Currently, the IEEE 802.11e task group has been working on a draft proposal for a QoS-aware MAC (Medium Access Control) protocol considering several differentiation mechanisms still under investigation ([25]) while the development of a higher-speed extension to 802.11b is undertaken by the 802.11g task group.

The ad-hoc communication method of 802.11 is the Distributed Coordination Function (DCF), which provides for a Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) access protocol; on the contrary, the alternative access method based on the Point Coordination Function (PCF) provides for a controlled access of the stations through a polling scheme performed by a central point coordinator thus not being ad-hoc. As for the ad-hoc mode DCF, according to the CSMA mode of operation each station senses the channel to determine whether some other station is transmitting. The collision avoidance mechanism is based on two techniques: the employment of the Inter-Frame Space (IFS) and the backoff algorithm. If the channel is found to be idle for a time interval exceeding the Distributed IFS (DIFS), the station starts transmitting, while if the channel is busy the transmission is deferred and scheduled at a time after a Backoff Interval (BI) randomly selected between a minimum Contention Window period (CW_{min}) and a maximum period (CW_{max}). An exponential backoff is adopted: the difference CW between CW_{min} and CW_{max} is doubled each time a collision occurs till CW_{max} is reached. The backoff timer is decreased till zero as long as the channel remains idle while it is frozen as a transmission is detected and activated again when the channel gets back to the idle status. Since collisions can not be detected by the transmitting station, an acknowledgment (ACK) is sent by the receiver to confirm the transmitted packet has been received uncorrupted and free by collisions. The ACK frame is sent after the channel is idle for a Short IFS (SIFS) lasting less than the DIFS to allow ACKs to be transmitted immediately and without entering the backoff procedure.

In order to alleviate the well-known hidden-terminal problem, causing possible collisions once transmission has started particularly in case of longer data packets, a three-way hand-shake procedure can be additionally employed by stations to access the channel. In this case, a further collision avoidance method has been introduced as extension of the basic access scheme. According to this mechanism, the transmitting station — once gained the channel and before starting transmission — contacts the receiver by sending a Request-To-Send (RTS) packet and the receiver accepts the request by answering with a Clear-To-Send (CTS) packet. All stations within the range of at least one of the two (receiver or transmitter) listen to RTS or CTS and thus defer their transmission for the duration indicated in both RTS and CTS and, if no collisions have occurred, transmission is initiated. Obviously collisions may still occur during the transmission of the (short) RTS and CTS packets but are avoided during data transmission. The brought drawback of the RTS/CTS mechanism is its less efficiency since the channel is acquired within the whole range of both the transmitter and the receiver, this resulting in the existence of the so-called exposed nodes whose transmission is inhibited although it would not collide.

In spite of the advantages of the DCF of being simple, easy to implement and suitable for most data applications, it has not been designed to support QoS thus showing poor performance when applied to delay and bandwidth sensitive applications. To this end, the draft proposal of the 802.11e task group has introduced two mechanisms able to support QoS requirements: the Enhanced Distributed Coordination Function (EDCF), which is derived from the DCF and provides for service differentiation via priorities thus operating according to an ad-hoc mode, and the Hybrid Coordination Function (HCF) which employs a polling scheme modified from the PCF's one and performed by a centralized controller, the Hybrid Coordinator (HC).

1.2.2 Bluetooth

The Bluetooth technology ([26]) is a *de facto* standard whose specifications are released by the Bluetooth Special Interest Group (SIG), founded in 1998 by a group of industrial leaders in telecommunications, computing and networking, specifically Ericsson, IBM, Intel, Nokia and Toshiba. In 1999, four more members added — 3Com Corporation, Lucent Technologies, Microsoft Corporation, Motorola Inc. — constituting with the previous five the Core Promoters of the Bluetooth SIG. Also the IEEE 802.15 Working Group for wireless PANs has approved its first standard derived form the Bluetooth specifications [27].

At the radio layer, the Frequency Hopping Spread Spectrum (FHSS) transmission technique is adopted operating in the ISM $2.4\ GHz$ band where 79 radio frequency channels are defined spaced $1\ MHz$ apart. The time axis is structured into slots each lasting $0.625\ ms$ and a Time Division Duplex (TDD) scheme is adopted.

The fundamental building block of a Bluetooth network is the *piconet* which is formed up to 8 active stations, one having the role of master and the others of slaves and having a gross bit rate of $1\ Mbit/s$. The master has the task of scheduling the access to the channel according to a polling scheme. As a result the channel access is contention-free and regulated by a central entity, the master; nevertheless, the communication mode is still ad-hoc since the election of the master is performed in a distributed fashion by the mobile stations. Specifically, a Bluetooth unit willing to start a data transmission enters an inquiry procedure in order to discover other Bluetooth units within its operating space by continuously sending an inquiring message and waiting for possible answers. At the end of the inquiry procedure the unit has acquired the Bluetooth device addresses of the units in its neighboring and estimated their clocks. When the unit actually wants to activate a new connection, it starts running a paging routine distributing its own Bluetooth device address and clock. The unit starting the paging is elected the master while the paged unit will be the slave. Once the paging procedure has been completed, the master and the slave are synchronized each other and can enter the connection state but the data transmission will actually take place according to the polling mechanism controlled by the master.

There exist two types of physical links: the Synchronous Connection-Oriented (SCO) and the Asynchronous Connection-Less (ACL) ones. The former supports a symmetric point-to-point connection of the circuit-switched type by means of two consecutive time-slots, one for master-to-slave and one for slave-to-master transmissions. The latter is a sort of packet-switched connection supporting point-to-multipoint transmission from the master to the slaves with reliable delivery of data thanks to a fast Automatic Repeat Request (ARQ) scheme. As for the polling scheme, the master unit polls a station by sending it either a data or a NULL packet: in case of SCO link the polling of a unit is periodic with time period equal to 6 slots, while ACL links are managed according to an asynchronous polling. A possible scheduling algorithm indicated by the specifications to be adopted by the master for the decision of the slaves' polling order is the Round Robin scheme, according to which the Bluetooth units are polled in a cyclic order; of course other solutions are possible in order to improve performance.

Besides the piconet, the Bluetooth specifications define a further networking structure, the *scatternet*. A scatternet is an interconnection of independent piconets having overlapping coverage areas and is dynamically built in an ad-hoc mode when some so-called inter-piconet units belong to more than one piconet at the same time. A main feature of scatternets is that an inter-piconet unit can communicate with the different piconets it belongs to in a time-multiplexing mode. Currently, just the notion of scatternet is defined in the Bluetooth specification while the relevant construction mechanism is not provided, this representing an open research issue.

1.3 Distributed access control

Wireless MAC protocols can be classified according to the mode of operation into the three following classes ([28]):

- random access protocols,
- guaranteed access protocols,
- hybrid access protocols.

With the formers, nodes have to contend for access to the medium and their data are vulnerable to collisions in case of contemporary transmissions of multiple nodes. Thus these protocols need to define specific rules to apply in order to resolve access contentions. On the contrary, with the guaranteed access ones nodes transmit in an orderly manner, for example in a round robin fashion and are thus contention-free. As for the hybrid access protocols, the data transmission of a node requires to perform two phases: a random access based one during which contentions among nodes are solved and the relevant data transmissions are scheduled and a contention-free guaranteed access used for transmitting data.

Our focus is on MAC protocols able to operate in an ad-hoc network and thus distributed. In this context, random access protocols are applicable as they do not need of a central scheduler. A distributed guaranteed access protocol could operate by exchanging tokens but in a wireless system token passing protocols would suffer from poor robustness and huge overhead of token recovery due to frequent token losses; for these reasons, they are not commonly proposed for wireless access. An alternative guaranteed access protocol is based on a master-slave configuration where the master polls the slave nodes. This protocol as well as the hybrid ones require the existence of a station performing a centralized access control and thus are not distributed by definition. Nevertheless, Bluetooth represents an example of technology enabling ad-hoc networking and applying a centralized MAC protocol; this is possible since the election of the master node is performed in an ad-hoc fashion. In the following we provide a brief survey of the main issues and the typical solutions at the MAC level for ad-hoc networks, which are indeed distributed protocols.

Finally, a special notice merits the distinction between the two cases of single-channel and multi-channel air interfaces. Typically, distributed access protocol have been defined for single-channel wireless access. However, every single-channel MAC protocol can be extended to the multi-channel case in a straightforward manner since in this context it would represent the basic access procedure for the access to one of the multiple channels. What is additionally required is an algorithm to determine the channel on which attempt the access. In this view, the concept of *collision* is still valid referring to time-overlapping transmissions on the same channel while transmission on different channels are assumed to be separated.

The two basic components of a distributed random access protocol are:

- the access rule, on the basis of which the transmission attempt is scheduled;
- the contention resolution algorithm, defining the rules for resolving the possible collisions on transmission.

As for the contention resolution algorithm, a typical example is the binary exponential backoff approach which consists in doubling the time period to wait for a new access attempt after each collision.

ALOHA was the first protocol for packet radio networks and represents the unique example of distributed access protocol not employing the carrier sensing principle [5][6]. According to the ALOHA access protocol, all nodes are asynchronous and a node starts transmitting as soon as it has data to send. In order to determine whether the transmission was successful, the transmitter waits an acknowledgment from the receiver for a maximum time period equal to two times the propagation delay of the network; if the acknowledgment is not received, a backoff algorithm is run to schedule a further attempt of transmission. The maximum throughput achieved by ALOHA is quite poor (about 18%) and can be improved by partitioning time in slots; the resulting scheme is called Slotted-ALOHA (S-ALOHA). S-ALOHA requires a central clock synchronizing nodes and allows to halve the vulnerable transmission period thus doubling the efficiency (maximum throughput equal to about 37%) [29].

After ALOHA, the carrier sensing principle ”listen before transmitting” has been introduced as a more sophisticated access method still extremely simple and reducing the collision probability [30]. Carrier sensing consists in listening the channel in order to detect any ongoing transmissions and possibly deferring the own transmission. The intrinsic characteristic of carrier sensing to be local-dependent results in the existence of hidden nodes (i.e., nodes sensing the channel idle while being busy) and exposed nodes (i.e., nodes sensing the channel busy whereas their transmission would not cause any collisions). Such nodes play a fundamental role in CSMA protocols affecting their effectiveness.

CSMA/CA protocols adopt — besides the carrier sensing — some collision avoidance technique in order to avoid that all nodes waiting to transmit during a period of busy channel, contemporary access the channel as soon as it gets idle again. To this end, a random delay before starting data transmission is introduced. Actually, all CSMA protocols are not purely based on carrier sensing since they employ this basic method of avoiding collisions. In addition, two other mechanisms are used by CSMA/CA protocols which further minimize the probability of a collision. A first method introduces an out-of-band signaling in order to prevent hidden nodes. Typically this signaling consists in the transmission of a busy tone; when a node hears a busy tone, it avoid initiating a transmission. In general, a trade-off exists between reducing the number of hidden nodes and of exposed nodes. For example, in [31] busy tones are transmitted by all nodes listening to an ongoing transmission thus blocking the access to the channel in an area centered in the transmitter and of radius twice its range. As a result, hidden nodes are completely eliminated at the expense of an increased number of exposed nodes and of a reduced efficiency of the protocol. A second collision avoidance mechanism is based on a three-way hand-shake. Before data transmission, the transmitter and the receiver carry out the RTS-CTS exchange and nodes listening to one of the two messages defer their transmission [32]. An ACK message is returned by the destination node in case of successful reception of data. An improvement of this scheme is achieved by using *virtual carrier sensing* ([33]) where time fields are added to the RTS and CTS packets indicating the duration of the current transmission.

1.4 Distributed QoS support at the MAC level

In the context of ad-hoc networking, in order to support a variety of applications and to provide differentiated service quality, QoS mechanisms are required at the MAC layer. Since the adopted medium access mechanisms are distributed, QoS provision needs to be distributed as well. The current distributed MAC protocols, based on the carrier sensing principle, are simple to implement, lack of synchronization among nodes and provide for a random access to the medium; these characteristics result in no guarantees for resources and fair access. Actually, there are no-built in mechanisms to support priority, guaranteed delay bounds or throughput.

A network able to support QoS provides a level of ensuring data delivery with different levels associated to different classes of traffic. The QoS support stands on three main functions:

- the mapping of the QoS parameters from one layer to the next;
- the admission control, used to determine whether the request of QoS can be supported by the network, given the amount of resources currently available;
- the allocation of suitable resources according to the requested QoS level.

So far, neither QoS mapping nor admission control have been widely investigated in the framework of ad-hoc networks. As for the function of resource allocation, the two typical methods are resource reservation, generally employed by centralized protocols, and prioritization, which instead can be used in distributed protocols. Actually, only resource reservation protocols can guarantee provision of *deterministic* QoS while prioritization ones can only assure *soft* QoS, that is service quality without any a-priori strict performance quantification.

The two main approaches of resource allocation with prioritization are the priority-scheduling and the fair-scheduling based ones [34]. In the following, an overview of the these two methods is provided. As discussed next, the main drawback of both is the overhead associated with using the waiting time (IFS and backoff interval) to differentiate traffic classes.

1.4.1 Priority-based QoS support

The common idea exploited by various proposals for QoS support based on priorities is to allow faster access to the channel to traffic classes having higher priorities. The means of pursuing this is allocating a smaller waiting time (IFS) or a smaller backoff interval (at least on average). In conditions of heavy load generated by traffic with higher priority, low-priority one does not succeed in fairly accessing the channel due to the lack of a mechanism providing throughput differentiation.

There exist several proposals based on assigning a smaller waiting time to high-priority traffic (e.g., see [35] and [36]). In some of them, after the IFS a small random time is added in order to avoid collisions of frame belonging to the same traffic class. The very problem of these schemes is related to their inability of guaranteeing fairness among different priority classes. Moreover, the adoption of the backoff algorithm in case of collisions could eliminate the priority provided by the IFS level.

Another group of solutions consists in modifying the backoff algorithm in order to differentiate traffic classes in terms of speed in accessing the medium. Unfortunately such schemes cause variability in delay and throughput due to the randomness of the backoff interval and, similarly to the previous schemes, are unfair. The idea is that different priority classes adopt different contention windows so that they select different backoff intervals. The contention windows can be either only differentiated but partially overlapping or completely separated. In the first case the service differentiation depends on the amount of overlap among the contention windows of the different classes. Actually the backoff intervals result differentiated only on average while, for example, it might happen that a higher priority class selects a backoff interval longer than the one of a lower priority class. In case of contention window differentiation, this is due to the partial overlapping of the ranges within which the backoff interval is selected. However, also if the used contention windows are initially separated, this separation could not be valid in time: this would be the case of a high-priority class experimenting a number of collisions much greater than the one of a low-priority class thus updating — according to the backoff algorithm — its contention window to a range overlapping with that of the second class. As a result, enabling QoS by differentiating the backoff algorithm leads to inconsistency in desired behavior over time.

1.4.2 QoS support using fair scheduling

Fair scheduling algorithms aim at partitioning the network resource fairly among flows in proportion to given weights. Instead of statically binding channel access to the priority, the waiting time to access the medium (i.e., either the IFS value or the backoff interval) is dynamically regulated according to a suitable algorithm assuring fair opportunity to each service class.

Some proposals move from the observation that the throughput is inversely proportional to the size of the contention window. For example, in [37] the contention window is modified based on the difference between the experienced throughput and the desired one. When the actual throughput is smaller then the target, the contention window size is decreased thus compensating the relevant traffic flow assigning it higher priority; vice versa in case the current throughput is higher than the desired amount. Since this mechanism uses the contention window, it suffers from the variability of throughput and delay. According to another proposal ([38]), an opportunity to transmit first is assigned to traffic classes having an higher ratio between the packet length and their weight; in particular, a backoff interval is picked which is proportional to this ratio. A drawback of this scheme is associated with using the backoff interval, thus incurring in the overhead due to the increased waiting time for backoff. A final example belonging to this family of scheduling algorithms is represented by the proposal in [39] which is based on the concept of deficit round robin ([40]) and on a suitable regulation of the IFS parameter. A deficit counter is maintained which is positively updated at a rate equal to the required throughput while it is reduced by the size of the transmitted frames. Thus this counter is a metric of the missed transmission opportunities of a certain traffic flow and the relevant value is mapped on a suitable IFS value, larger counters resulting in smaller values of the IFS and vice versa. In order to eliminate the fluctuations in throughput and delay, the authors propose as basic scheme not to adopt the backoff algorithm; however, the combined use of IFS and the backoff interval further improve performance although the regulation of the parameters is quite critical.

Chapter 2

Joint distributed power and radio resource control for QoS support

2.1 Introduction

The typical MAC approach for distributed wireless networks is based on the carrier sensing principle and the collision avoidance mechanism, as discussed in the previous Chapter. The relevant MAC protocols focus on the problem of hidden and exposed nodes and attempt to solve or at least mitigate it. Basically, they are based on the idea that two transmissions partially overlapping in time produce a collision at the receiver and the way of avoiding packet corruption at the receiver is to completely eliminate collisions. In turn, the collision avoidance method consists in making nodes transmit in separated time periods, thus not allowing at all any kind of parallelism in transmission. The channel usage is classified in two hard states: idle or busy. The main limits of such protocols concern the fact that nodes acquire the radio resource in their whole transmission range and that they transmit at the maximum allowed power. As a consequence, the channel results busy in the whole acquired area — whose extension is the maximum one — and the resulting channel utilization is quite low.

Today, power controlled MAC is becoming the most attractive proposal as access scheme providing efficient use of the radio spectrum for wireless ad-hoc networks [17][18][41][42]. According to this approach of access control, power control is mainly introduced as a mechanism to be jointly used with MAC procedures in order to increase the radio channel utilization. Specifically, the idea consists in managing node power levels with the two goals of:

- guaranteeing a target transmission quality to each ongoing communication, given the current interference level;

- getting each transmitting node to emit a power level such that the other transmissions' quality is not degraded too much.

Therefore, the nodes' power levels are set to their minimum values able to guarantee a target transmission quality; as a consequence, not only more than one link can access the channel at the same time but also the battery mean life time is increased since each node acquires the minimum transmission range needed to reach its counterpart. While power control is quite commonly used in multi-channel air interfaces — in particular the CDMA-like ones — it results a novel idea when applied in single-channel systems. In the access to a single channel, power control exploits the ”space-division” among different communications which can supply for the absence of a multiple access technique — like Time Division (TDMA), Frequency Division (FDMA) as well as Code Division Multiple Access — in distinguishing the different transmissions. In particular, in wireless systems with a distributed architecture, there may be a higher degree of space-separation among nodes belonging to different communications than in ones with a centralized architecture.

In the perspective of power controlled MAC, as the ”hard” concept of collision is removed and substituted by the ”soft” one of interference, the collision avoidance mechanism is turned into an interference control one by means of power control technique; whereas the former approach controls *whether and when* nodes can transmit, the latter regulates *the amount* of transmissions measured in terms of brought interference.

In defining the problem of the distributed power controlled access, a major classification concerns the distinction between single-hop and multi-hop networks. In this latter case, the problem leads to the definition of a suitable routing strategy which is power aware or power control based and the management of the single hop can be seen as a basic function needed for extending to the multi-hop case [43]. In this thesis, our focus is on single-hop networks.

2.2 Model of the distributed power controlled access

We define a reference model for the formalization of the power controlled access problem. We consider a number of nodes structured in a certain topology where a *link* connecting two nodes with a given versus represents a communication from the source node to the destination one. A static situation is considered without introducing mobility of nodes; this assumption is equivalent to suppose that the node mobility as well as other causes of dynamic variations in the considered scenario (e.g., fading phenomena of the radio channel) evolve on a time scale longer at least than that of the access procedure.

Let us consider a topology constituted by a number N of unidirectional links. In a general case of air interface, i.e., either single or multi channel ([44]), the links will interfere each other, the i-th one perceiving a SIR value γ_i given by the following expression:

$$\gamma_i = \frac{P_i \cdot G_{ii}}{\sum_{j=1,j\neq i}^{N} P_j \cdot G_{ij} + n_i} \tag{2.1}$$

where the used notation is referred to the link entity according to the following:

P_i is the transmission power of the i-th link's source node;

G_{ii} represents the path gain g_{ii} of the link i;

G_{ij}, with $i \neq j$, is the path gain g_{ij} from the j-th link's source node to the i-th link's destination node divided by the processing gain (which will be greater than one in case of multi-channel CDMA-like systems, equal to one in case of single-channel systems);

n_i is the noise power at the i-th links destination node.

As for the path gain, we assume that this accounts for the distance attenuation as well as for shadowing and multi-path fading effects. In case of CDMA-like air interface with variable spreading factor, the expression in (2.1) implicitly contains also the data rate. In fact, the processing gain of the i-th link by which is divided each path gain in G_{ij} is derived as the ratio between the basic system data rate, $R_\circ$, and the data rate of the i-th link itself, R_i; thus it results $G_{ij} = g_{ij} \cdot \frac{R_i}{R_\circ}$ with $i \neq j$. Also the noise power, n_i, can be expressed as a function of the data rate, R_i, and of the total noise power before modulation, $n_\circ$, being $n_i = n_\circ \cdot \frac{R_i}{R_\circ}$.

Although the discussion could be continued referring to the general case, from now on only CDMA-like air interfaces will be considered which are able to provide a number of channels mutually interfering with variable data rates. Thus, the SIR expression in (2.1) can be written in the following way where the data rate is explicitly shown:

$$\gamma_i = \frac{P_i \cdot g_{ii}}{\frac{R_i}{R_\circ} \cdot (\sum_{j=1, j\neq i}^{N} P_j \cdot g_{ij} + n_\circ)} \tag{2.2}$$

In the following, we formalize the power controlled access problem within a theoretical framework, while the issues relevant to possible implementation schemes in an ad-hoc network will be discussed in depth in the following Section, along with proposals found in literature.

We study a topology where N given links are to be established with requirements on the desired SIR, γ^T, and on the data rate, R. The target SIR level is in relation with the expected BER (Bit Error Rate), where the functional relationship between the two quantities essentially depends on the considered modulation scheme.

The evaluation of *admissibility* of a configuration of N links consists in finding out, if there exists, a proper set of transmission powers $\{P_i\}_{i=1,\ldots,N}$ that satisfies for each link i=1, ..., N its requirements in terms of rate R_i assuring $\gamma_i \geq \gamma_i^T$. More precisely, this problem can be formalized according to the following matrix form which allows to identify the well-known condition for the existence of a feasible solution:

$$\begin{cases} (\mathbf{I} - \mathbf{F}) \cdot \mathbf{P} \geq \mathbf{u} \\ \mathbf{P} \geq \mathbf{0} \end{cases} \tag{2.3}$$

where:

I is the $N \times N$ identity matrix;

P is the column vector of the N transmission powers;

F is a $N \times N$ matrix which depends on the current system topology (e.g., nodes mutual distances); in particular F_{ii}=0 and $F_{ij} = \frac{R_i}{R_\circ} \cdot \frac{\gamma_i^T \cdot g_{ij}}{g_{ii}}$ with $i \neq j$;

u is an N-dimensional column vector essentially related to noise powers ($u_i = \frac{R_i}{R_\circ} \cdot \frac{\gamma_i^T \cdot n_\circ}{g_{ii}}$).

In equation (2.3) the inequalities between vectors have to be taken as inequalities component by component.

The existence of a feasible solution of problem (2.3) consists in a condition for the eigenvalue of Perron-Frobenius (i.e., the maximum modulus eigenvalue) of **F**, ρ_F, and is $\rho_F < 1$. If a solution of problem (2.3) exists, then the minimum power configuration is called Pareto-optimal solution (e.g., see [44]) and is provided by the following expression:

$$\mathbf{P}^* = (\mathbf{I} - \mathbf{F})^{-1} \cdot \mathbf{u} \tag{2.4}$$

which has the property that every other power configuration consists in values that are not lower than their corresponding Pareto-optimal ones. In particular any other solution can be expressed as $\mathbf{P}^+ = (\mathbf{I} - \mathbf{F})^{-1} \cdot (\mathbf{u} + \Delta\mathbf{u})$ where $\Delta\mathbf{u}$ is a column vector of N real positive values.

In order to characterize the feasible solutions of problem (2.3), let $\mathcal{D}$ denote the relevant domain. Since real scenarios are typically power constrained, we are interested in identifying solutions not exceeding the maximum level of transmission power P_{max}^{dv} that radio devices can emit. Therefore, an admissible topology is associated with a non-empty domain $\mathcal{D}$ of solutions which is composed by:

- the Pareto-optimal solution $\mathbf{P}^*$ allowing to match exactly the desired SIR levels at the minimum transmission powers;
- the set of solutions having form $\mathbf{P}^+$ and such that $\mathbf{P}^* < \mathbf{P}^+ \leq \mathbf{P}_{max}^{dv}$ (denoted by $\mathcal{D}^-$) whose employment does not exceed the maximum powers and reaches SIR levels above the targets;
- the set of solutions having form $\mathbf{P}^+$ whose employment would exceed the maximum power at least for one link (denoted by $\mathcal{D}^+$), that is $\mathbf{P}^+ \in \mathcal{D}^+ \Longleftrightarrow \exists i \in [1, N]$ such that $P_i^+ > P_{max}^{dv}$.

When the topology is admissible but the activation of all links requires to set some transmission power above the maximum P_{max}^{dv}, it happens that the set $\mathcal{D}^-$ is empty and the set $\mathcal{D}^+$ includes also the Pareto-optimal solution $\mathbf{P}^*$.

An access scheme based on the Pareto-optimal solution can be implemented by either a centralized or a distributed procedure. In the centralized case, an access point should act as a central controller *i*) collecting all information required to build the matrix $\mathbf{F}$ and the noise vector $\mathbf{u}$, *ii*) computing the Pareto-optimal solution $\mathbf{P}^*$ according to equation (2.3), *iii*) signaling to the involved stations the transmission powers to be used. While steps *ii*) and *iii*) are quite simple to be implemented, the first one presents several crucial issues since the knowledge of the matrix $\mathbf{F}$ and of the noise vector $\mathbf{u}$ in turn requires the knowledge of the reciprocal path gains among all nodes. As a consequence, either a localization procedure or a distributed procedure of estimation of the reciprocal distances among nodes is needed. For these reasons, a centralized approach seems hardly feasible in a real scenario, especially considering that the tasks *i*), *ii*), *iii*) should be performed frequently in relation to the arrival/departure/movement of nodes. Some works address distributed implementations of Pareto-optimal solutions; also in this case there are several aspects that introduce high complexity in the system, as it will be discussed in the following Section.

2.3 A survey of solutions for distributed power controlled RRC

In this Section a survey is provided of the main distributed solutions for access control based on power regulation. Proposals found in literature are sometimes quite heterogeneous since they provide for either a power control algorithm to adopt in a distributed radio access or a complete protocol of radio resource control for managing rate and power. In any case, such proposals contribute to the general topic of RRC with power control by suggesting possible methodologies. Thus, from now on we will refer to these solutions as proposals for *Power Controlled RRC* (PC-RRC) schemes.

A possible classification of distributed RRC schemes based on power control focuses on the employment or not of explicit signaling among the different links' nodes. In this context, two main classes can be identified:

1. PC-RRC schemes based exclusively on measurements (like proposals in [44], [45], [46], [47], [48] and [49]);

2. PC-RRC schemes based on both measurements and signaling among different links (like solutions provided by [50], [51] and[52]).

As for proposals belonging to the first class, the common idea is that a link can extract information on the system just by performing measurements. In particular in [48] a local (hence distributed) probing scheme is developed aiming at discovering admissibility of the new link just by “comparing” interference measurement results before and after activating the transmission on the link itself: a link evaluates the impact of its entrance on the others — which will adapt to the new interference — and decides whether it is admissible. In [44] it is proposed a distributed power control algorithm which protects active links against the interference brought by new access attempts. Each link just applies a rule for power updating on the basis of the SIR currently measured: the algorithm guarantees maintenance of a target SIR during updating. However, a weakness of such works is that technological bounds on the maximum power a device can emit are not taken into account. This problem can not be overcome when links operate only on the basis of measurements. In fact, a link evaluates the possibility to enter the system on the basis of the reaction that other links have when it starts a transmission. However, this reaction could be feebler than needed, since some links might have saturated their maximum power value thus reacting in a limited way. As a consequence, the admission decision could wrongly succeed causing the drop of power saturated links, which have not been able to overcome the new increased interference.

Other approaches face and overcome the problem related to maximum powers by means of explicit *interlink signaling*. The adopted solution consists in protecting links by maintaining margins with respect to the target SIR requirements and explicitly signaling the amounts of these margins in the system so that they are used for the admission of new links. These strategies result more suitable for a distributed framework since they avoid global reconfiguration of power levels at the entrance of each new link and more robust in protecting links from drops due to maximum power saturation. Maintenance of a margin implies that each link can tolerate positive extra interference due to new accesses and also absorb link quality variations due to “unpredictable” phenomena (e.g., radio channel altering and mobility). Obviously a trade-off exists between setting large margins, thus accommodating a high number of QoS links but contemporarily transmitting elevated power values, or fixing the margins at very low values thus reducing system flexibility and number of contemporary active links. We point out that in these approaches an explicit inter-link signaling is required since a link willing to be established must regulate its transmission power in accordance to margins of its neighboring links. This signaling shall be supported by a common broadcast channel and can consist in a data packet or in a tone conveying information on margins (see [52]); moreover, margins exchange could be done periodically (like in [52]) or on demand (like in [50]).

A further classification concerns the way powers are managed each time a new link tries to be established: the power management can be either *global* or *incremental* [50]. A global management implies that the system shall reconfigure powers used by all the links every time a new link enters the system or leaves it. On the contrary, an incremental scheme does not reconfigure previously assigned power levels but proceeds in an incremental way: the decision whether a new link can be established is based only on the current system situation, that is not globally re-configured. An incremental strategy can be much simpler to be implemented; on the other hand, in principle, it could lead to a less efficient resource utilization.

The definition of these two power management approaches can be formalized in more exact terms according to the following. Let r^T be the target range for the SIR levels, i.e., the range of values that the power control must make every link's SIR reach; in general, the target range r^T may clash on a single value. We consider k active links at power levels $\{P_i\}_{i=1,\dots,k}$. Thus the configuration of the considered topology can be described according to the following statement:

$$\text{Given } n_\circ \text{ and } \{g_{ij}\}_{i,j=1,\dots,k}, \{P_i\}_{i=1,\dots,k} \text{ are such that } \gamma_i^{(k)} \in r^T, i = 1, \dots, k. \tag{2.5}$$

where $\gamma_i^{(k)}$ represents the SIR level of the i-th link in presence of the k considered ones. Now, let us consider a $(k+1)$-th link to be established.

In case of a global PC-RRC, the problem to be solved consists in properly setting the *whole* set of power levels $\{P_i\}_{i=1,\ldots,k+1}$ and can be formulated in the following way:

$$\text{Does there exist } \{P_i\}_{i=1,\ldots,k+1} \text{ such that } \gamma_i^{(k+1)} \in r^T, i = 1, \ldots, k+1? \tag{2.6}$$

We can observe that in this case it does not matter whether r^T is actually a range of values or just a single target value. By definition, the global problem requires that, when a new link has to be activated, all powers are reassigned in order to get each link to match the target r^T again. Thus, each time the network topology changes, the global allocation rule makes the network move to a new configuration of transmission powers. The implementation of a global PC-RRC requires the definition of a distributed power reconfiguration mechanism which is quite a hard challenge since a complete knowledge of the network topology would be needed by each link, which is a non-realistic assumption in a distributed scenario. Typically, schemes based only on measurements fall into the class of global power management and try to overcome this issue by adapting to SIR/interference measures. The common features of such schemes is that at the entrance of a new link, the others have to adapt to the new brought interference by a power control algorithm which converges over time to the desired solution. Anyway, not all the proposals can guarantee consistence with the SIR requirements during the updating phase (like in [48]) and also a convergence problem of the power reconfiguration algorithm generally arises. The major example of global strategy based only on measurements is a scheme reconfiguring transmission powers according to the Pareto-optimal solution $\mathbf{P}^*$ as new links add to the network (like in [48]). Unfortunately, as already discussed, such a scheme can not assure that the power configuration $\mathbf{P}^*$ actually belongs to the domain $\mathcal{D}^-$ of power levels not exceeding the maximum one. The scheme proposed in [44] represents an example of a global scheme reconfiguring transmission powers at a solution $\mathbf{P}^+$ in order to assure links protection from new accesses; also in this case, the only employment of measurements to drive the reconfiguration process does not assure to remain within the domain $\mathcal{D}^-$ giving rise to possible link drops.

When we consider an incremental PC-RRC, the main difference in the problem to be solved with respect to the global approach concerns the fact that the power configuration in (2.5) must be maintained while only the new link's transmission power P_{k+1} can be suitably chosen as expressed by the following problem formulation:

$$\text{Does there exists } P_{k+1} \text{ such that } \gamma_i^{(k+1)} \in r^T, i = 1, \dots, k+1 \text{ given } \{P_i\}_{i=1,\dots,k} \text{ of (2.5)?} \quad (2.7)$$

Due to the additional interference generated by the $(k+1)$-th link, the SIR values $\gamma_i^{(k+1)}$, $i = 1, \dots, k$, are less than their correspondent $\gamma_i^{(k)}$, $i = 1, \dots, k$. Therefore, the $(k+1)$-th link can be activated if and only if the target r^T is actually a range of values. In fact, if this is the case, each link out of the k ones perceives a *margin* with regard to the minimum desired SIR and thus can tolerate a non-zero extra interference level before its SIR gets out-of-target. The definition of a distributed incremental PC-RRC must provide for the information exchange about these margins among nodes of different links, so that a new link is locally and autonomously able to find a feasible solution of problem (2.7); therefore, the incremental approaches fall into the class of schemes based on both measurements and inter-link signaling. In general, the contrary is not true: schemes based on measurements and signaling can be either global or incremental, although proposals found in literature do not introduce the possibility to reconfigure transmission powers after access and are thus to be considered incremental approaches. Schemes that fall into the class of incremental strategies (such as [50], [51] and[52]) always adopt as power configuration solutions $\mathbf{P}^+$. Since an inter-link signaling exchange is provided, there exists the possibility of verifying that the identified solution belong to the domain $\mathcal{D}^-$ thus avoiding drop of power saturated links.

Table 2.1 summarizes the main characteristics of the discussed strategies.

2.4 Our proposal of a power controlled RRC with admission control for ad-hoc networks

RRC mechanisms for the QoS support based on suitable configuration of transmission powers allow to:

- establish and maintain wireless links by adapting power levels on the basis of the current

Table 2.1: Comparison of different distributed power controlled RRC schemes

Strategies	**Interaction among different links**	**System efficiency**	**Access decision time**	**Global vs. incremental management of powers**	**Overall complexity**
Based exclusively on measurements with continuous power adjustments [44] [45] [46] [47] [48] [49]	Not required	Aim at converging or at approaching an optimal power assignment	Depends on the convergence speed	Global	High
Based on measurements and signaling with power selection performed at the access of a new link [50] [51] [52] [this proposal]	Required (via signaling)	The overall power assignment results in a sub-optimal configuration	Depends on the signaling phase duration	Incremental (also ”partially global” solutions would be possible)	Low

interference condition,

- make links achieve differentiated QoS requirements in terms of rate and target SIR (see for example [46]),
- mitigate interference and thus improve channel reuse.

However a complete definition of a scheme providing QoS needs not only of a proper resource management but also of an admission control of links willing to enter the system (as discussed in Section 1.4.2). Specifically, as for the three main functions of a QoS aware RRC — namely QoS representation, admission control and resource assignment (see Section 1.4.2) — in this work we focus on all the three, differently by main proposals in literature (for example see [45] and [46]). In particular, we adopt the following assumptions and methodology.

QoS representation. We assume that negotiated service requirements can be expressed at the RRC layer in terms of desired SIR threshold below which links' SIRs should not drop, and data rate. We point out that this metric is simple and at the same time implicitly includes also QoS parameters like BER (whose performance is linked to the one of SIR) and packet transmission time (strictly related to the data rate).

Admission Control. We explicitly address the problem of the admission control of a new service request; the relevant major challenge is that in the context of ad-hoc networking this function must be performed in a distributed way, that is autonomously by each link whose nodes are attempting to access the radio resource. The distributed nature of the admission control impacts the definition of both the relevant algorithm and protocol. The scheme we propose is based on both measurements and inter-link signaling.

Resource assignment. In order to privilege the robustness of the admission control and the simplicity of the relevant implementation, still aiming at a flexible and efficient system, we pursue an incremental-like approach. In addition, we chose to manage resource by a reservation scheme rather than a prioritization one, so that QoS can be actually *guaranteed*. The resource to be assigned is defined by the two quantities of data rate and power: while we assume that the requirement on the latter must be strictly fulfilled (that is the negotiated amount of data rate is reserved), as for the former it can be flexibly and freely chosen being constrained only by the other links' toleration to additional interference. An appealing feature of the proposed scheme is that further flexibility is added by permitting that in case of failure of the admission control with given values of the QoS parameters, a sort of backoff procedure can be performed relaxing the QoS requirements, that is lowering the SIR level and/or the data rate to negotiate.

The incremental strategy we select belongs to the class of ones based on keeping margins with respect to the threshold SIR, while maintaining the desired data rate, and on signaling the values of these margins which are managed for the admission of new service requests. The major innovative aspects are two:

1. the selection of powers and margins during the admission control phase is performed with the aim of balancing their values with reference to the active links' parameters;

2. this self-reconfigurable approach is proposed for networks whose architecture can be either completely ad-hoc or with infrastructure.

This latter point will be shown in Chapter 3 by referring to a specific case study, while in this Section we focus on the context of ”pure” ad-hoc networking. The balancing of the transmission parameters goes in the direction of increasing the system efficiency and reducing the link block probability, defined as the probability that the system can not accept an incoming link due to saturation of margins of already active links.

In Section 2.4.1 we present the algorithm of our PC-RRC with the admission control rule, while Section 2.4.2 is devoted to describe an implementation of this proposal.

2.4.1 The distributed algorithm

In our scheme we pursue the goal of supporting QoS by introducing the so-called *Maximum Extra Interference* (MEI), that is the amount of interference that can be tolerated by a link without endangering the negotiated QoS level. In other words, when the MEI is zero no other interfering emissions can be tolerated; when the MEI is positive other links can be activated, provided that the overall interference they produce does not make the MEI go below zero. The aim of our admission control mechanism is primarily to guarantee that the MEIs of all active links in the system are never negative. In addition, for efficiency reasons, our admission control procedure tends to balance all MEIs within an area, so as to avoid that bottlenecks regions and regions where high MEIs are available coexist.

The MEI level perceived by the i-th link out of N, denoted as M_i, depends on the QoS parameters, γ_i^T and R_i, the power level set for transmission, P_i, and the current interference conditions according to the following expression:

$$\gamma_i^T = \frac{P_i \cdot g_{ii}}{\frac{R_i}{R_\circ} \cdot \left(\sum_{j=1, j\neq i}^{N} P_j \cdot g_{ij} + M_i + n_\circ\right)} \tag{2.8}$$

with notation as defined in Section 2.2.

The scheme we propose proceeds in an incremental way: given a set of active links, the two entities — transmitter and receiver — willing to establish a new link take the access decision by measuring the system. Once verified the admissibility of the new link, the links' power levels will be maintained at a power configuration included in the domain $\mathcal{D}^{-}$, thus assuring that the transmission powers are within the maximum one P^{dv}_{max}. Power levels are computed on the basis of the set of current MEI values $\{M_i\}_{i=1,\ldots,N}$ according to:

$$\begin{cases} \mathbf{P}^{+} = (\mathbf{I}-\mathbf{F})^{-1}\cdot(\mathbf{u}+\Delta\mathbf{u}) \\ \Delta u_i = \frac{R_i}{R_\circ}\cdot\frac{\gamma_i^T\cdot M_i}{g_{ii}}, i=1,\ldots,N \end{cases} \tag{2.9}$$

As stated in Section 2.2, the power configuration $\mathbf{P}^{+}$ provides for power levels greater than the corresponding Pareto-optimal ones and can be expressed as $\mathbf{P}^{+} = \mathbf{P}^{*} + \Delta\mathbf{P}$ where $\Delta\mathbf{P} = (\mathbf{I}-\mathbf{F})^{-1}\cdot\Delta\mathbf{u}$ is a vector of positive elements. The MEI levels $\{M_i\}_{i=1,\ldots,N}$ can be expressed as functions of the additional powers $\{\Delta P_i\}_{i=1,\ldots,N}$ employed by the N links as:

$$M_i = \frac{R_\circ}{R_i}\cdot\frac{g_{ii}\Delta P_i}{\gamma_i^T} - \sum_{j=1,j\neq i}^{N} g_{ij}\Delta P_j \tag{2.10}$$

This equation highlights a tradeoff: the additional power ΔP_i used by the i-th link increases the relevant MEI M_i while, on the other hand, the $\{\Delta P_j\}_{j=1,\ldots,N,j\neq i}$ of the other active links reduce its amount. Furthermore, MEI is inversely proportional to the QoS parameters; as an example, the support of a high data rate requires the acquisition of an elevated MEI.

As for the maximum power that a device can use, we account both for the device's capabilities related to technological issues (P^{cap}_{max}) and to regulatory body's upper bounds (P^{reg}_{max}), considering that typical technologies for ad-hoc networking will employ license-free frequency bands, which are likely to be regulated by means of emission masks:

$$P^{dv}_{max} = \min\{P^{cap}_{max}, P^{reg}_{max}\}. \tag{2.11}$$

The admission control rule for an $(N+1)$-th link, given N active ones, consists in the comparison between the minimum power $P_{min,N+1}$ needed to satisfy the link's QoS requirements (γ^T_{N+1} and R_{N+1}) on the basis of the current interference level at the receiver $I_{N+1} = \sum_{i=1}^{N} P_j \cdot g_{N+1j}$, and the maximum power $P_{max,N+1}$; this latter is the maximum level within the upper bound in equation (2.11) and satisfying the constraints imposed by the MEI levels of the N

active links (that should not reduce to zero when the new link is activated). The minimum and maximum power are derived according to the two following equations:

$$P_{min,N+1} = \frac{R_{N+1}}{R_\circ} \cdot \frac{\gamma_{N+1}^T}{g_{N+1N+1}} \cdot (I_{N+1} + n_\circ) \tag{2.12}$$

$$P_{max,N+1} = \min\left\{P_{max}^{dv}, \min_{1\leq j\leq N}\left\{\frac{M_j}{g_{jN+1}}\right\}\right\} \tag{2.13}$$

If the access can take place, i.e., if $P_{min,N+1} \leq P_{max,N+1}$, then a suitable transmission power level is selected for the activation of the link within the range $[P_{min,N+1}, P_{max,N+1}]$ according to the aforementioned criterion of keeping balanced the MEI values. In fact, it is to be noticed that the access probability, defined as Prob$\{P_{min,N+1} \leq P_{max,N+1}\}$, is as higher as greater the MEI values $\{M_i\}_{1\leq i\leq N}$ are. This depends on the minimum taken in (2.13) where the lowest MEI constitutes a bottleneck for further accesses. In our incremental approach, at the access of the $(N+1)$-th link, the optimal working point $\mathbf{P}^+$ can be tracked by suitably choosing P_{N+1}. In particular, the optimal power $P_{opt,N+1}$ for the new link will be the one that maximizes the minimum MEI. The activation of the $(N+1)$-th link impacts the active ones reducing their MEIs; these reductions as well as the MEI level acquired by the new link depend on the transmission power P_{N+1} according to the following formulas:

$$M_i^+ = M_i^- - P_{N+1} \cdot g_{iN+1}, 1 \leq i \leq N \tag{2.14}$$

$$M_{N+1} = \frac{R_\circ}{R_{N+1}} \cdot \frac{P_{N+1} \cdot g_{N+1N+1}}{\gamma_{N+1}^T} - I_{N+1} - n_\circ \tag{2.15}$$

where in (2.14) M_i^- and M_i^+ denote, respectively, the value of the MEI for the generic i-th link before and after the $(N+1)$-th link's access at power P_{N+1}.

An example of the potential impact of a new link's transmission in terms of MEIs is shown in Figure 2.1 for the case $N = 2$ where also the optimal power $P_{opt,N+1}$ is indicated (in the example $P_{opt,3}$). In particular, the considered example highlights that at the access of the new link (link 3) the most limiting MEI, as for the impact on the maximum power amount $P_{max,3}$, does not necessarily belong to the link with the lowest MEI before the access (i.e., link 1 having

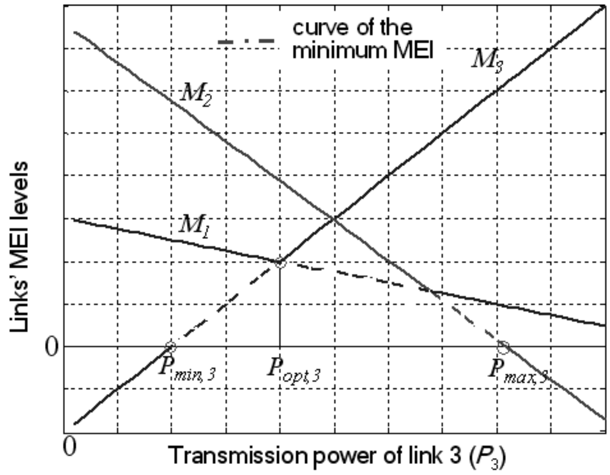

Figure 2.1: MEI levels as a function of the entering link's transmission power

$M_1^- < M_2^-$) but to the link with the worst combination of MEI value M_i^- and path gain of the new transmitter toward its receiver (in the example link 2 which results in a M_2^+ decreasing faster than M_1^+ and thus giving rise to a stricter constraint on the maximum power).

The optimal power value is computed according to the following equation:

$$P_{opt,N+1} = \min_{1 \leq i \leq N} \left\{ \frac{M_i^- + I_{N+1} + n_\circ}{g_{iN+1} + \frac{R_\circ}{R_{N+1}} \cdot \frac{g_{N+1N+1}}{\gamma_{N+1}^T}} \right\} \tag{2.16}$$

The selected power $P_{opt,N+1}$ actually represents just a sub-optimal choice since the access is managed in an incremental way (without re-configuring transmission powers of the active links). Although such a strategy is less efficient than a global one (as pointed out in Section 2.3), it results quite simple to be implemented.

Further efficiency improvements could be achieved by a reconfiguration of powers after a new access. In accordance to the incremental procedure, such reconfigurations should be partial — i.e., should concern just a subset of transmission powers — performed step-by-step varying one power level per time and still based on a local optimization. The main motivation for varying transmission powers during links' lifetime is the double advantage it would bring in: on one hand, the optimization process would be carried out by a number of incremental operations of power adjustment rather than the only power selection at a new access; on the other hand, the reconfiguration process could balance again the MEIs which during the lifetime of the network will generally evolve to unbalanced values and will be also consumed by new accesses.

The way of performing a power reconfiguration is very similar to the power selection procedure at a new access. First the link to be reconfigured in transmission power has to be selected according to a suitable optimizing criterion; secondly its transmission power is changed at the optimal value maximizing the minimum MEI. The impact on the effectiveness of the procedure in terms of number of accommodated links strictly depends on the choice of the link to be reconfigured and on the number of consecutive reconfigurations carried out between two subsequent access trials.

2.4.2 Implementation in the context of ad-hoc networks

In the following we aim at presenting a possible implementation of the proposed admission control scheme and we highlight the operations performed at the transmitter (TX) and the receiver (RX) of a link that should be activated. To this end, we identify the flow charts (see Figure 2.2) of the functions performed to establish the link with desired QoS parameters (target SIR γ^T and bit rate R).

First, we remark that the proposed scheme is based on the assumption that the node that would act as TX must acquire current MEI values of its neighboring receivers (named in the following n_RXs in order to not be confused to the candidate receiver RX of the device that is trying to set-up a link). Acquisition of MEIs allows the device willing to establish a link as TX to compute the maximum power it can emit so that the n_RXs still maintain their negotiated QoS parameters even if extra interference will be introduced in the system by the new link. As a consequence, the implementation of the access scheme requires an explicit inter-link signaling: each device will signal on a broadcast common channel its current MEI level. It is to be noticed that in equation (2.13) we indicated that the MEIs are acquired for all the N links in the systems. However, since the impact that a transmission could have on a generic node is inversely proportional to the distance of this node from the TX, it is sufficient that the MEIs are acquired only from the neighboring devices (n_RXs that are in a number less or equal to N).

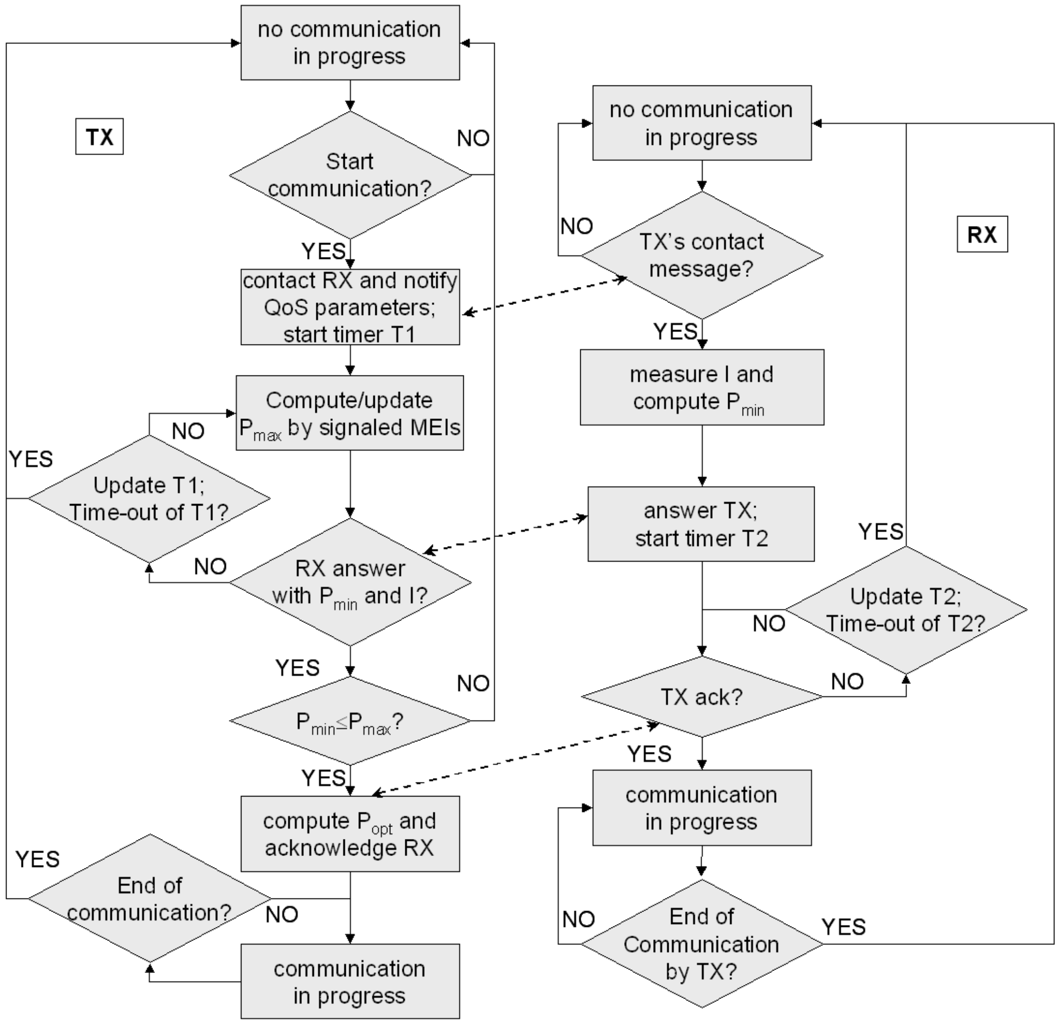

Figure 2.2: Flow charts of the TX's and RX's operations

The admission decision and the activation of a new link requires a cooperation of both its TX and RX; besides, also the receivers in the TX's neighboring are involved since it is required that they signal their MEIs. In Figure 2.2, the dotted lines between the two flow charts indicate signaling exchange between the TX and RX involved in the activation of their communication link. The TX has the task of computing the maximum power on the basis of the current MEI values acquired by the broadcast signaling of its n_RXs. Since the TX will actually listen just to the MEIs signaled by the receivers in its neighboring, the maximum power computation at the TX assures that the considered MEIs concern only links which it could actually disturb. Moreover, the TX has to estimate the reciprocal path gains between itself and the n_RXs; this estimation is derived by the signaling messages transporting the MEIs by comparing the relevant transmitted and received powers: the first one can be either a-priori known or explicitly signaled in the same message while the second one is measured. The task of the RX consists in measuring the perceived interference (I) and thus computing the minimum transmission power on the basis of the desired SIR and bit rate. These operations are carried out once the TX has contacted the RX notifying also the desired QoS parameters. The RX will answer to the TX communicating the values of the minimum transmission power and of the measured interference. The admission rule — i.e., the comparison between the minimum and the maximum power levels — is checked by the TX which acknowledges to the RX the access decision. If the access is not possible (since it results $P_{min} > P_{max}$) it is also possible to relax the QoS request by reducing, for example, the desired rate R (see equation (2.12)). On the contrary, if the access is possible, the computation of the optimal power is performed by the TX since it requires, besides the interference at the RX, the knowledge of the current neighboring MEIs. In Figure 2.2, we indicated the employment of two timers, T1 in the TX's procedure and T2 in the RX's procedure. T1 is used by the TX when it is waiting for the RX's answer to its first contact message; if the answer does not arrive within the T1's time-out, the TX argues that the contact's attempt failed and the procedure of the link activation is ended coming back to the status of "no communication in progress". As for T2, this timer is started by RX after its answer to TX and specifically when it begins waiting for the TX's acknowledgement of the activation success. If the timer T2 expires, RX assumes that the activation attempt failed and enters the status of "no communication in progress".

In order to summarize the entire procedure for the access of a new link, let us briefly list the main steps carried out by the TX and the RX without explicitly mentioning the timers involved (see Figure 2.3).

step 1. The TX contacts the RX to start a communication towards it notifying the required QoS parameters (γ^T and R).

step 2. Once received the contact message, the RX estimates the path gain with the TX, measures the received interference and thus calculates the minimum power P_{min} (according to equation 2.12) needed to activate the link.

step 3. In the meanwhile the TX listens to the broadcast common channel gathering the signaled MEIs and thus calculates the maximum power P_{max} (see expression in equation 2.13) that can be used to activate the link.

step 4. The RX answers to the TX's contact message sending the value calculated for P_{min} and the amount of measured interference I;

step 5. The admission control takes place by the comparison between P_{min} and P_{max} carried out by the TX.

step 6. In case of success of the procedure, the optimal power level P_{opt} is calculated according to equation (2.16) on the basis of the MEIs currently acquired, the interference I at the receiver and the QoS parameters (γ^T and R).

A final observation concerns a possible backoff procedure that can be entered as the access fails. The flowcharts shown in Figure 2.2 refer to the case that only one access attempt is performed. Nevertheless, this basic procedure can be simply extended including the possibility to perform a number of access attempts according to a suitable backoff algorithm. In particular, an interesting enhancement of the access procedure could be obtained by making the TX relax the required QoS in terms of γ^T and/or R and then trying again the access procedure. Of course, the actual possibility to change the QoS parameters strictly depends on the considered application and on its tolerance to performance varying in a range.

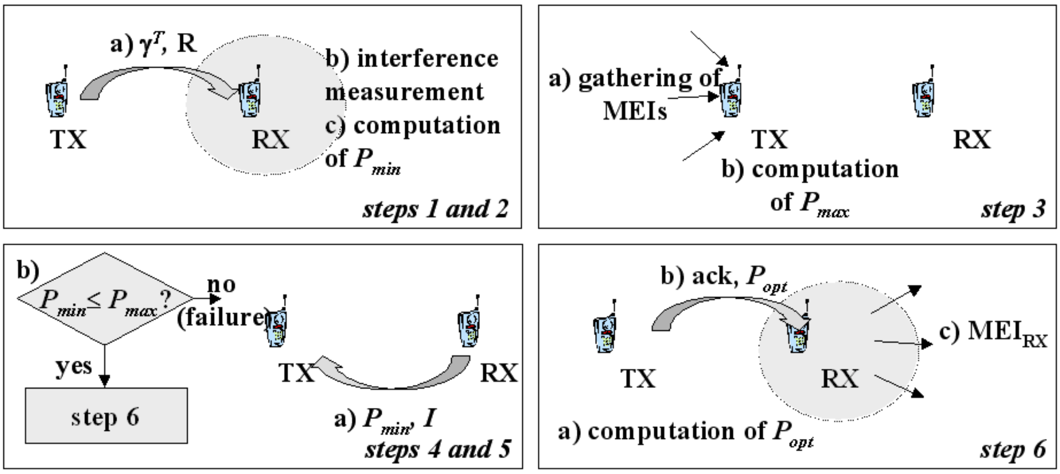

Figure 2.3: Main steps of the admission control protocol

In Chapter 3 we will consider an example of infrastructure wireless network where the communication paradigm is still ad-hoc like. In order to show how the proposed distributed PC-RRC can be flexibly employed also in this context, we will define the relevant implementation highlighting how the functions defined by the flow charts of TX and RX are carried out by mobile stations and access points in a peer-to-peer fashion.

Chapter 3

A case study: an UWB access network

3.1 Introduction

The present Chapter aims at illustrating an application of the proposed distributed PC-RRC as well as demonstrating its flexibility as ability to be applied in scenarios which differ from the one considered — i.e., the ad-hoc networks — with regard to the architectural characteristics. Specifically, while the previous Chapter focuses on the context of *pure* ad-hoc networks, here we consider a system — the one proposed in the IST WHYLESS.COM project ([19]) — whose architecture is centralized; nevertheless, the relevant RRC is still designed according to an *ad-hoc communication paradigm*. Actually, the definition of ad-hoc network could be extended than the one provided in Section 1.1 by including also networks having indeed an infrastructure; their feature of *ad-hoc* arises when this infrastructure is not exploited in order to provide connectivity, that is the network life does not depend on the aid of the infrastructure itself and communications are established according to a peer-to-peer model [42].

3.1.1 The IST WHYLESS.COM project

The IST WHYLESS.COM project has the goal of studying the potentiality of the technique of radio transmission UWB for the development of an *Open Mobile Access Network* — i.e., an access network based on a versatile air interface providing an open platform to support QoS aware services through a network architecture which combines the UWB radio access procedures with a stateless IP QoS paradigm [20].

The UWB technology ([13]) is an emerging paradigm both in the field of radar applications and digital communications. UWB systems are mostly based on Impulse Radio (IR) technology, which has recently reached an appreciable degree of development so as to be able to support high data rates with low power consumption and low complexity in terms of transmission/reception operations [14][53]. By combining a transmission over a wide radio spectrum band with low power and pulsed data, UWB causes less interference than conventional narrowband radio and offers potential to hit the market in unlicensed bandwidths. In this context, on one side UWB radio systems provide the ability to potentially operate worldwide across frequency bands occupied by existing narrowband systems; on the other side, they also offer great flexibility in managing a given cell capacity by adapting to either a large number of low-rate nodes or a smaller number of high-rate nodes, depending on the requirements of the application [54]. Today it is clear that UWB is a promising field to create small, high bit rate transceivers that could be used for a wide set of applications in the telecommunication field, from WLANs to ad-hoc networks, from IP mobile-computing to multimedia-centric applications. A consistent amount of literature has been dedicated to the analysis of UWB transmission/reception principles and of its relevant performance [55][56][57][58]. Besides these key issues, the challenge in using UWB technology in wireless communication systems lies in the development of multiple access techniques and radio resource sharing schemes.

UWB appears a competitive technology for radio access using an ad-hoc communication paradigm and, when exploited in this context, has the potential of bringing some specifically suitable advantages, thanks to a few UWB features matching exactly the requirements needed to design an open radio access based on the ad-hoc model. First of all, UWB can provide high data rates also in indoor, dense multipath environments [59][60], as it is expected from the technologies of future generation radio systems. An additional feature of UWB is its flexibility in the reconfiguration process of data-rate and power, due to the availability of a number of transmission parameters which can be tuned to better match the requirements of a service request. As far as radio-terminal equipment is concerned, this is generally cheaper than the equipment for traditional technologies, as the structure of the receiver is extremely simple due also to the absence of a carrier. Moreover, IR calls for the synchronization of communicating transmitter-receiver pairs but works efficiently even though different links in the network are asynchronous; this feature is particularly suitable in a network with a distributed RRC, where the absence of an infrastructure would imply a highly complex synchronization of all nodes.

3.2 The UWB technology

In WHYLESS.COM, UWB based on Impulse Radio is considered according to which extremely short pulses (of duration $0.1 \div 1.5\ ns$) are transmitted giving rise to wide spectral occupation in the frequency domain (bandwidth from near DC to a few GHz). The typical pulse, named *monocycle* and denoted by $g(t)$, is the building block for data transfer that is commonly obtained by using a Pulse Position Modulation (PPM). In a binary context a logical ”zero” is transmitted by one monocycle centered at time $t_\circ$, $g(t - t_\circ)$, whereas a logical ”one” is transmitted by the monocycle shifted by δ seconds, $g(t - (t_\circ + \delta))$. The time axis is structured in time frames of duration T_f, (typically about $100\ ns$), which in turn are divided into N_h short time bins (whose duration is denoted by T_c). The multiple access is based on the adoption of pseudo-random Time Hopping (TH) codes whose elements are chosen among N_h possible T_c-shifts within the period T_f [53]. The information of one bit (or symbol) is associated with N_s consecutive pulses transmitted at the pulse repetition time $\frac{1}{T_f}$; therefore, the obtained bit rate is $R = \frac{1}{N_s \cdot T_f}$. The period of a code word is denoted as N_p and generally it is $N_p > N_s$. Figure 3.1 reports an example of two users which transmit employing two different TH-code words: whereas the first user employs the TH-code $\{1, 3, 0, 2, \ldots\}$, the second one uses the word $\{3, 2, 5, 4, \ldots\}$. Each element of a code word corresponds to one of the possible N_h time shifts in the T_f period. We assumed that the two users were synchronous both with the T_f and with each other. Generally, in an ad-hoc network both assumptions are not satisfied. However, though the users are not synchronized with each other and the TH-codes are chosen in a pseudo-random way, catastrophic collisions are not very likely to occur while just mutual interference arises and is indeed compensated by suitably modulating the data rate and the transmission power, that is

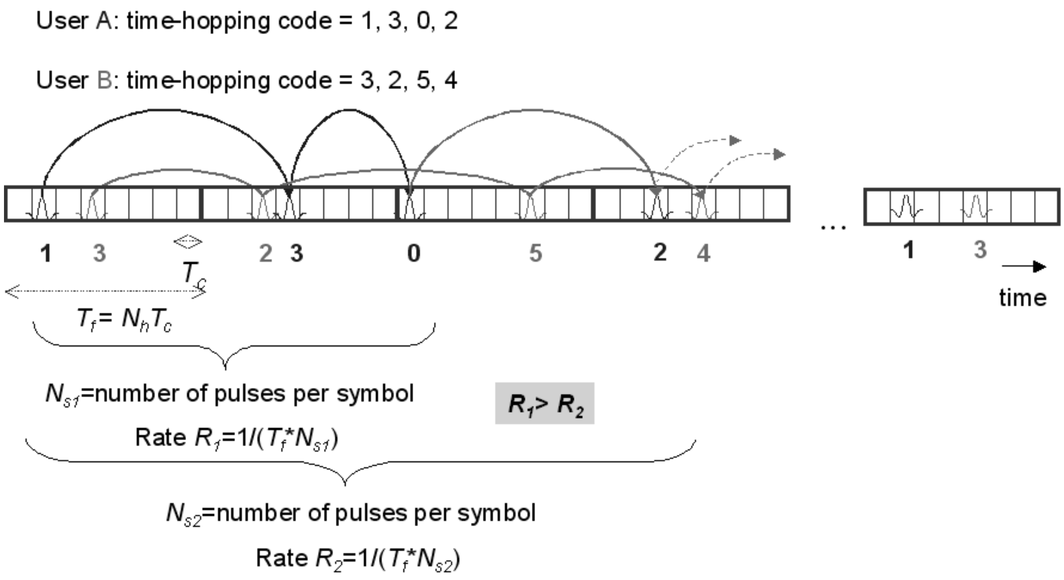

Figure 3.1: UWB multiple access scheme

transmitting several monocycles for the same bit [53].

The SIR for UWB is computed under the hypothesis of gaussian approximation of the multi-user interference ([53]) and can be expressed as a function of:

- the amplitudes $\{A_i\}_{i=1,\ldots,N}$ (measured in $Volt$) applied to the monocycle $g(t)$ used by the N links;
- the correlation m_p between the monocycle $g(t)$ and the receiver waveform $\nu(t)$, i.e., $m_p = \int_{-\infty}^{+\infty} g(t) \cdot \nu(t)\, dt$;
- the parameter σ_a^2 derived as $\sigma_a^2 = \frac{\int_{-\infty}^{+\infty} \left(\int_{-\infty}^{+\infty} g(t-s) \cdot \nu(t)\, dt \right)^2 ds}{T_f}$;
- the mean square value of the thermal noise n(t), $p^{(n)} = E\{n^2(t)\}$ (measured in $Volt^2$); for a load Z_n with resistive part equal to $Re\{Z_n\}$ at temperature T (expressed in degrees $Kelvin$) and in a frequency band of width Δf, it results $p^{(n)} = 4kT\Delta f \cdot Re\{Z_n\}$, where k denotes the Boltzmann's constant (whose value is $1.38062 \cdot 10^{-23}\ Joule/K$).

Specifically, the SIR value γ_i is determined for the i-th link, which employs a number $N_{s,i}$ of pulses per bit, according to the following formula:

$$\gamma_i = \frac{A_i^2 \cdot (N_{s,i} m_p)^2 \cdot g_{ii}}{\sum_{j=1, j\neq i}^{N} A_j^2 \cdot g_{ij} \cdot N_{s,i}\sigma_a^2 + \frac{p^{(n)}}{\Delta f} \cdot N_{s,i} m_p} \tag{3.1}$$

This SIR formula can also be expressed as a function of the transmission powers $\{P_i\}_{i=1,\ldots,N}$ (measured in $Watt$) of the N links by introducing the relevant relationship with the monocycle energy E_W and the amplitudes $\{A_i\}_{i=1,\ldots,N}$ and referring to a load $Z_\circ$ with resistive part equal to $Re\{Z_\circ\}$:

$$P_i = \frac{1}{T_f}\int_0^{T_f} (A_i \cdot g(t))^2 \, dt \cdot \frac{1}{4Re\{Z_\circ\}} = \frac{A_i^2 \cdot E_W}{T_f} \cdot \frac{1}{4Re\{Z_\circ\}}, \; E_W = \int_0^{T_f} g^2(t)\, dt \tag{3.2}$$

The expression obtained for the SIR γ_i of the i-th link, whose bit rate is $R_i = \frac{1}{N_{s,i} \cdot T_f}$, is then:

$$\gamma_i = \frac{P_i \cdot g_{ii}}{R_i \cdot (\sigma^2 T_f \cdot \sum_{j=1, j\neq i}^{N} P_j \cdot g_{ij} + \eta_\circ)} \tag{3.3}$$

where the two symbols $\eta_\circ$ and σ^2 has been introduced respectively given by $\eta_\circ = \frac{p^{(n)}}{\Delta f} \cdot \frac{1}{4Re\{Z_\circ\}} \cdot \frac{E_W}{m_p}$ and $\sigma^2 = \frac{\sigma_a^2}{m_p^2}$. As for $\eta_\circ$, it can be put in relation with the two-sided spectral density of the available noise power $N_\circ = \frac{kT}{2}$ (measured in $Watt/Hz$) according to the formula $\eta_\circ = 2N_\circ \cdot \frac{E_W}{m_p} \cdot \frac{Re\{Z_n\}}{Re\{Z_\circ\}}$.

As it can be noticed, different UWB parameters have an impact on the SIR: this value, in fact, besides increasing with power as in a generic wireless system, depends on the pulse shape via σ, on the TH period via T_f and on the number of pulses per bit via R.

Possible values of the UWB parameters are reported in Table 3.1 [53].

Table 3.1: Possible values of the UWB parameters

m_p	$1.7464 \cdot 10^{-10}\ s$
T_f	$100\ ns$
σ_a^2	$0.6 \cdot 10^{-22}\ s^2$
$\frac{p^{(n)}}{\Delta f}$	$6.5276 \cdot 10^{-21}\ Volt^2 s$
E_W	$1.08 \cdot 10^{-10}\ s$

3.3 The reference architecture

The WHYLESS.COM reference scenario for the support of QoS services is based on a clear separation between the provision of communication services and the provision of information contents. This architecture includes a logical entity, called Network Resource Broker (NRB), which interfaces these two aspects.

The communication infrastructure is composed of different Administrative Domains (AD), IP-based. Each AD is managed by a Network Resource Manager (NRM) that controls the information transport resources within the AD. The NRB performs resource control at an *inter-domain* level, collecting information about the ADs' status by means of their (respective) NRMs and offers services to the information content platform (Application Service Providers, ASPs). Once service contracts have been stipulated, the service requests sent to the NRB are translated into requests of resource allocation to the communication infrastructure; at this stage, *intra-domain* resource management procedures are involved.

The intra-domain resource management is executed in two phases:

- the ID-phase, which consists in the IDentification of the available resource within an AD; the results of the ID-phase are reported in Per Domain Behavior (PDB) tables [61] and collected by the NRB to perform inter-domain routing;
- the AC-phase, which concerns the Admission Control of a new flow in the AD, thus effecting decisions taken during the previous ID-phase .

The reference architecture is composed of wired ADs and wireless ADs (WAD). Each domain is associated with its own NRM, having the task of guaranteeing the negotiated services. In turn, a WAD is constituted by Access Points (AP), Radio Terminals (RT, that is the radio device of a mobile user), Access Network Routers (ANR) and a number of standard Core/Edge Routers (CR/ER) (see Figure 3.2). In the radio segment, the desired versatility for an *open access* is obtained by employing UWB and avoiding rigid cell and frequency planning schemes. The AP is a layer 2 entity that evaluates the available resources during the ID-phase and is involved in the admission control of RTs during the AC-phase. The set of radio entities (APs and RTs) that can

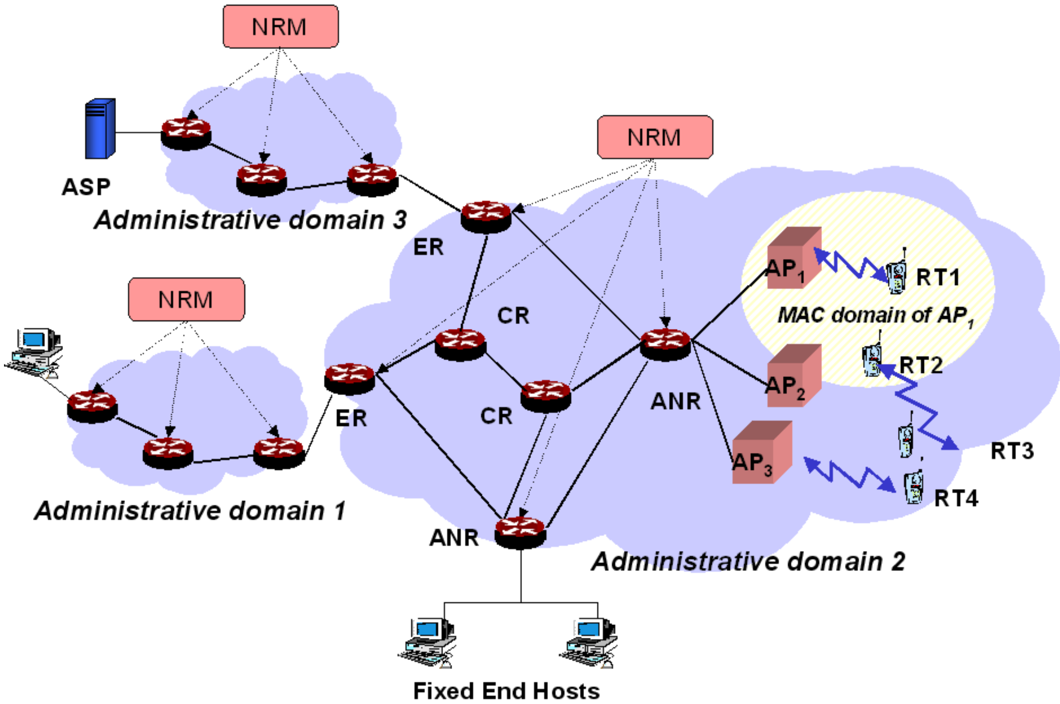

Figure 3.2: Architecture of the WHYLESS.COM communication infrastructure.

communicate with one another, make up and are in association with a so-called MAC-domain. The ANR, as a layer 3 entity, carries out functions concerned with IP protocol procedures. In general, an ANR is in association with several APs and is the only entity of the radio access part interacting directly with the IP backbone.

Within each domain, specific functions concerning the resource management have to be performed during the ID-phase and the AC-phase. Although the interaction between the NRB and the NRMs follows a centralized approach, this way of operation does not influences the strategies to be applied within the ADs. Instead, the resource management schemes of WADs and ADs should be as similar to each other as possible. In fact, if procedures relevant to the fixed part can easily interact and be integrated with those of the wireless part, then the WAD's NRM can interact with the NRB following the same procedures of the wired AD's NRMs. In addition, the NRB should perceive in the same way fixed and wireless domains for an easy interworking. This goal is rather challenging due to the different characteristics of the two worlds as regards their architectures and the nature of the resources to be managed. With this goal in mind, within the WHYLESS.COM project two resource management strategies have been developed, one designed for fixed ADs and for the fixed part of a WAD, and one designed for the wireless part of a WAD, respectively. The common underlying philosophy of these two solutions consists in a distributed approach, based on measurements carried out at the IP and at the MAC layer, respectively.

3.4 The distributed power controlled RRC applied to the WHYLESS.COM architecture

In the network architecture considered in the WHYLESS.COM project, RRC is involved during both the ID-phase and the AC-phase as regards intra-domain mechanisms for the UWB segment of a WAD. The employment of an ad-hoc communication model in the air interface results in an easy interworking among the RRC procedures pertaining different MAC domains (which might belong to either different WADs or to the same). In addition, a flexible feature of the developed RRC is to make coexist UWB links extending the access to the services of the fixed network and *local* communications. The ID-phase is invoked only when a user asks for one of the services provided by the fixed network; in this case the system has to select the best AP for serving this request, to negotiate with the user the service quality level and to calculate the relevant price. Instead, when a local communication has to take place between two RTs, directly the AC-phase is entered. Thus, the adoption of an ad-hoc model for admission control in both kinds of UWB links introduces indeed the flexibility to make simply coexist radio links attaching to the fixed network and peer-to-peer local communications.

In specifying how applying the proposed distributed PC-RRC in this context, which is no more a pure ad-hoc network, the issues to face are:

1. the evaluation of the resource available in the system given the current load (see Section 3.4.2); this estimation constitutes the basis for the selection of a proper AP among a number of potential ones;

2. the admission control of a service request with an AP selected at the end of the ID-phase for serving the request itself (see Section 3.4.3).

To this end, the first two steps to carry out are *i*) mapping the access model defined in Section 2.2 for a general radio interface on the case of UWB multiple access scheme and *ii*) specifying the completely ad-hoc version of the PC-RRC when UWB is adopted. Once the definition of the proposed strategy has been provided for UWB, we can proceed to discuss the application to the WHYLESS.COM architecture by specifying the two issues given above, 1 and 2.

The UWB SIR expression provided by equation (3.3) can be mapped onto the general one of equation (2.2) by posing the following relationships between the system basic rate $R_\circ$ and the noise power $n_\circ$ one one hand, and the UWB parameters σ^2, T_f and $\eta_\circ$ on the other hand:

$$\begin{aligned} R_\circ &= \tfrac{1}{\sigma^2 T_f} \\ n_\circ &= \tfrac{\eta_\circ}{\sigma^2 T_f} \end{aligned} \tag{3.4}$$

The MEI level, M_i, perceived by the i-th link out of N is then defined according to the following expression:

$$\gamma_i^T = \frac{P_i \cdot g_{ii}}{R_i \cdot (\sigma^2 T_f \cdot \sum_{j=1, j\neq i}^{N} P_j \cdot g_{ij} + \sigma^2 T_f \cdot M_i + \eta_\circ)} \tag{3.5}$$

Also the matrix form of the power controlled access — provided by equation (2.3) — can be expressed for UWB as functions of the UWB parameters according to the following formulas for the matrix **F** and the vector **u** :

$$\begin{cases} (\mathbf{I} - \mathbf{F}) \cdot \mathbf{P} \geq \mathbf{u} \\ \mathbf{P} \geq \mathbf{0} \\ F_{ij} = R_i \gamma_i^T \cdot \frac{\sigma^2 T_f \cdot g_{ij}}{g_{ii}} \\ u_i = R_i \gamma_i^T \cdot \frac{\eta_\circ}{g_{ii}} \end{cases} \tag{3.6}$$

Therefore, the solution $\mathbf{P}^+ = (\mathbf{I} - \mathbf{F})^{-1} \cdot (\mathbf{u} + \Delta\mathbf{u})$ adopted by the proposed PC-RRC is computed on the basis of a vector $\Delta\mathbf{u}$ having the i-th component given by:

$$\Delta u_i = R_i \gamma_i^T \cdot \frac{\sigma^2 T_f \cdot M_i}{g_{ii}} \tag{3.7}$$

and the i-th MEI level, M_i, as a function of the additional powers $\{\Delta P_i\}_{i=1,\dots,N}$ employed by the N links is:

$$M_i = \frac{g_{ii} \Delta P_i}{\sigma^2 T_f \cdot R_i \gamma_i^T} - \sum_{j=1, j \neq i}^{N} g_{ij} \Delta P_j \tag{3.8}$$

Finally, the minimum, maximum and optimal power levels for a further $(N+1)$-th link (provided by equations (2.12), (2.13), and (2.16) respectively) can be now expressed as:

$$P_{min,N+1} = \frac{R_{N+1} \gamma_{N+1}^T}{g_{N+1N+1}} \cdot (\sigma^2 T_f \cdot I_{N+1} + \eta_\circ) \tag{3.9}$$

$$P_{max,N+1} = \min \left\{ P_{max}^{dv}, \min_{1 \le j \le N} \left\{ \frac{M_j}{g_{jN+1}} \right\} \right\} \tag{3.10}$$

$$P_{opt,N+1} = \min_{1 \le i \le N} \left\{ \frac{M_i^- + I_{N+1} + \frac{\eta_\circ}{\sigma^2 T_f}}{g_{iN+1} + \frac{g_{N+1N+1}}{\sigma^2 T_f \cdot R_{N+1} \gamma_{N+1}^T}} \right\} \tag{3.11}$$

where $I_{N+1} = \sum_{i=1}^{N} P_j \cdot g_{N+1j}$ denotes the interference level at the new link's receiver.

3.4.1 The background broadcasting procedure

As in the ad-hoc version of the PC-RRC scheme, there exists the need of broadcasting in the system the information relevant to the current amount of active communications' MEIs. A background broadcasting procedure run by APs and RTs provides an interlink signaling exchange, so that these entities can detect and acquire information about neighboring radio entities and then employ such information to perform both the ID- and the AC-phases. Thanks to such broadcasting procedure, the AP can estimate the resource available in the domain and formulate service offers; these are collected by the NRM.

The broadcasting procedure exploits suitable Broadcast-packets (B-packs), which are continuously transmitted by APs and RTs via two dedicated control channels, supported by two different TH codes, one for the APs and one for the RTs. A major observation concerns the overhead required to signal the MEI levels, which is quite poor in the WHYLESS.COM system. In fact, hello messages broadcasted by both APs and RTs would be needed in any case in order to make nodes discover the topology: APs have to perform estimation of available resource on the basis of the set of potential users in their neighboring and of the current usage of the radio resource, whereas RTs need to discover the possible APs they can attach to for establishing a radio link. Thus the signaling of MEIs requires just to add a further field in these messages.

3.4.2 Identification of the available resource

The ID-phase provides the information about the current status of the domains in terms of resource availability; as for WADs, on the basis of this information an AP is selected to fulfill a specific user service request.

An AP can estimate the bit rate available for new uplink/downlink communications with a given service class (characterized by a certain SIR level) on the basis of the information collected by B-packs within its MAC-domain. In particular, the AP shall calculate the maximum rate, corresponding to the maximum power compliant with MEIs constraints, given the current interference status and the service class's SIR level.

This operation should be performed for each potential new communication and separately for downlink and uplink. Nevertheless, a possible simplification of the ID-phase can be achieved by referring to an imaginary RT, which is representative of the ones in the AP's MAC-domain; for example, this imaginary RT could be characterized by parameters calculated by averaging on the parameters themselves of the actual RTs, as we assume in the following. In particular, the estimated available bit rate for new downlink/uplink communications, $R_{av}^{dw/up}$, is computed by APs on the basis of the service class's SIR level, γ^T, according to the following formula:

$$R_{av}^{dw/up} = \frac{P_{max}^{AP/RT} \cdot g^{dw/up}}{\gamma^T \cdot (\sigma^2 T_f I^{RT/AP} + \eta_\circ)} \tag{3.12}$$

where the quantities $g^{dw/up}$, $P_{max}^{AP/RT}$ and $I^{RT/AP}$, which would depend on the RT location, are calculated by APs for the previously mentioned imaginary RT.

The values of the quantities needed to evaluate the available rate are obtained via interference measurements performed at RTs and APs, broadcasted together with MEIs' levels. Specifically:

- the path gain $g^{dw/up}$ is derived as the ratio between the received and the transmitted power of a RT's B-pack, for both downlink and uplink, assuming perfect symmetry of the radio channel; the power level used to transmit B-packs can be either fixed and known *a-priori* or explicitly signaled in the B-pack itself;
- as for the maximum power $P_{max}^{AP/RT}$, in case of downlink (P_{max}^{AP}) it is calculated directly by the AP on the basis of the gathered MEIs while in case of uplink (P_{max}^{RT}) the correspondent value of each RT is signaled by means of its B-pack and then the AP averages on the set of collected values;
- the current level of interference $I^{RT/AP}$ is measured by the AP and the RTs; for evaluating R_{av}^{dw}, the measured quantity I^{RT} has to be included in the B-pack by every RT.

A major observation concerns the simple way of estimating the available data rate for new potential services. This task, which is typically quite a challenging issue in radio systems, is made easier in the case of our RRC thanks to the adoption and management of MEIs, employed as e metric of additional resource that can be allocated.

At the end of the ID-phase, each AP has acquired information about the set of RTs which are its potential users. In the WHYLESS.COM architecture, this information shall be used as soon as one of the RTs will do a service request by means of its ASP. A service request is expressed by the user in *qualitative* terms and translated by the ASP in *quantitative* desired performance (requested transmission rate R and SIR level γ^T). At this stage, in case of several possible APs for serving the request, one of them is selected: in this procedure the NRB and the NRMs are involved. The criterion for selecting a specific AP and the procedural interaction among the NRB and the NRMs do not concern the RRC; rather at the level of RRC only the resulting choice of the serving AP for the given request matters. In general the selected AP is the one able to offer the ”best service” to the RT on the basis of a defined technical cost.

A generalization of this procedure provides for several possible offers to the user: for each possible AP, a different technical cost is computed on the basis of the ID-phase results and an offer with a different (economic) cost and thus price is presented to the user. In this case, the user has the possibility to choose among a set of offers characterized by a different trade-off between service quality level and price. Before the AC-phase takes place, a single serving AP is selected in any case: if the RT accepts the service offer, the ASP asks the NRMs to allocate the negotiated service level and the admission control procedure is started involving the chosen AP and the RT.

3.4.3 Admission control

When the AC-phase starts, both for local communications and for links with an AP of the infrastructure, the two nodes transmitter (TX) and receiver (RX) of the UWB link to establish are known as well as the required (negotiated) quality parameters (rate R and SIR γ^T). The admission control is performed in a pure ad-hoc fashion; this implies that also in case of uplink/downlink of a RT with an AP, the two radio nodes (RT and AP) act as *peer* entities; in other terms, from the point of view of the RRC functions, they lack of any hierarchical structure among each other.

The admission control procedure refers to the activation of a link with the given QoS parameters supported by a suitable TH code. In case of local communication, no further comments have to be added to the admission control procedure as described in the ad-hoc context (see Section 2.4.2). Instead, we aim at showing how this same procedure can be employed also for links with APs, highlighting the role acted by these.

Let us recall the admission control procedure described in Section 2.4.2 by means of the flowcharts of the TX’s and RX’s operations shown in Figure 2.2 and consider as an example the activation of an uplink. According to the described procedure, a RT entering an UWB domain and willing to establish an uplink with a discovered AP should first contact the AP in order to initiate the activation procedure. Then it will start listening to the broadcast channel in order to acquire the current MEI values of RTs and possible other APs in its neighboring. Then it will compute the maximum transmission power on the basis of the MEIs. Let us notice that APs and RTs operate in the same way according to a peer-to-peer communication paradigm. Since the RT is the transmitter part of the uplink, the admission control is autonomously performed by the RT itself thanks to the AP's cooperation which signals the minimum power required on the basis of its perceived interference. Thus, the distributed nature of the scheme stands in the fact that the RTs are actively involved in the check of the admission control rule; besides, also the collection of the information needed to perform the admission control requires a distributed cooperation of each node. In these features, it is evident the opposite approach in respect of cellular radio systems, where admission control functions are fully centralized in the Base Stations. When the set-up of a downlink is attempted, the AP operates as TX. Besides the computation of the maximum power it can emit, also the number of already active downlink communications is a component of the access decision rule (specifically, an AP shall also take into account scheduling and buffering resources it can provide for the downlinks support).

To conclude, we stress that the approach of such admission control scheme — designed according to an ad-hoc model and thus well adapting to radio systems transmitting in license-free frequency bands — is fully complementary in comparison with the one of cellular systems, where the radio resource is a-priori planned and partitioned among different operators and different cell owning to the same operator. In fact, the coexistence of neighbor APs (belonging or not to the same WAD) is achieved by means of a *self-configurable* scheme, in line with the ”ad-hoc philosophy”: the necessary regulation of the interference produced by the uplinks and downlinks of a given AP when admitting new links and allocating further radio resource, is automatically pursued by adapting to current MEIs' amounts of radio nodes (thus, also APs) in its neighboring. In other terms, the given AP does not need to know explicitly how many and what other APs are present in its neighboring but only the MEIs' values of the relevant uplinks and downlinks. We also remind that this information is not centrally stored at the relevant AP but is always broadcasted by the receiver of a link (the RTs for uplinks and the AP for each of the downlinks).

Chapter 4

Performance analysis

4.1 Simulation plan and considered simulation models

The performance study has been carried out having in mind the following objectives:

- showing the mechanism of the adaptive selection of MEIs trough an example of a network building up (Section 4.2.1);

- highlighting that indeed configurations of balanced MEIs get higher probability of access in respect of configurations of sparse MEIs (Section 4.2.2);

- quantifying the advantage on performance of the adaptive selection of MEIs in comparison with non-adaptive schemes on one hand, and the downgrading in comparison with techniques implementing the access rule based on the necessary and sufficient condition of admissibility (Sections 4.3 and 4.4); let us remind that the proposed access scheme renounces some performance in lieu of a simpler implementation and robustness in the maintenance of the QoS.

In the present Chapter, also some results relating the network model with UWB access of WHY-LESS.COM are shown (Section 4.5). In this case, the specific goal consists in demonstrating the possibility of employing the proposed access rule in order to quantify the available bit rate for further accesses and to select the point of radio access to the network on the basis of this evaluated quantity rather than on purely transmissive parameters, like the SIR or the received power.

In comparing the proposed access scheme to other strategies, we introduced the following notation:

- A-MEI (Adaptive MEI) denotes the proposed scheme of adapting the selection of the MEI to the current network status; in our simulations we did not introduced the power reconfiguration process;
- C-MEI (Constant MEI) refers to the selection of an initial constant MEI (as proposed in [50], for instance);
- MIN-P (Minimum Power) stands for an ideal scheme which implements the theoretical Pareto-optimal solution; the relevant procedure is assumed to behave ideally rejecting access requests that would force some links to reach the maximum power.

In the following Sections we introduce the parameter $M0$, which denotes the initial MEI that the first link in the network acquires. This quantity has an impact on performance that will be investigated. Here we remark that while for A-MEI $M0$ represents just the first link's MEI, for C-MEI it is the MEI that *each* link tries to acquire at the access.

The network topologies studied in the performance study represent a number N of links whose radio entities, transmitter and receiver, are randomly located in an area of $50\ m \times 50\ m$ in an ad-hoc fashion, that is according to a distributed topology. The QoS parameters we adopted are: link rate $R = 100\ kbit/s$ and target SIR $\gamma^T = 5$.

We take into account a general radio interface characterized by the SIR expression provided in (2.2) with the following setting and assumptions for the relevant parameters:

- frequency band $\Delta f = 50\ MHz$ and basic system bit rate $R_\circ$=50 $Mbit/s$;
- temperature noise in antenna of $300\ K$ plus a receiver noise figure of $10\ dB$, thus equivalent noise temperature T such that $kT = -194\ dBW/Hz$ and $n_\circ = kT\Delta f = 1.9906{\cdot}10^{-12}\ W$;
- maximum transmission power allowed per device $P^{dv}_{max} = 1\ W$;

- path gain model as a function of the link extension d according to $g = (\frac{\lambda}{4\pi d})^2$ with wavelength $\lambda = \frac{c}{f_c}$ where f_c is the central frequency and c is the propagation speed ($c = 2.99792 \cdot 10^8 \; m/s$); we assume $f_c = 2.4 \; GHz$.

4.2 Dependance of performance by the MEI management scheme

4.2.1 Example comparing the two strategies of fixed and adaptive MEIs

We present an example showing the difference and advantage of the proposed rule of admission control, A-MEI, in respect of the scheme of constant initial MEIs, C-MEI. Let us consider a sequence of five links willing to activate. In Tables 4.1 and 4.2 — referring respectively to A-MEI and C-MEI — the MEIs in correspondence of the receiver of each active link are shown (the values are normalized by the initial value $M0$). Note that a MEI equal to infinite characterizes a non-active link. In particular the considered topology is represented at four steps corresponding to the access of the first link (a), of the second (b), of the fourth (c), and of the fifth (d). In case A-MEI is adopted (Table 4.1), the entering link acquires a normalized MEI equal to the minimum one (see for example link 4 in respect of link 1 in (c)). Instead, in case of C-MEI (see Table 4.2), each new link enters acquiring a constant maximum MEI, i.e. $M0$. Thus at the step (b), with A-MEI the two links achieve equal MEIs while with C-MEI the second achieves a normalized MEI equal to 1 causing the maximum reduction on MEI of link 1. In Table 4.2 at step (d) the previous unbalanced MEI condition leads to a block of the network for future accesses since link 1's MEI reduces to zero due to the access of link 5 at the maximum power. The disadvantage of unbalanced MEIs is evident in the fact that the other links 2, 3, 4 and 5 continue maintaining useless high MEIs while their reduction would increase MEI of link 1 thus unblocking the network.

4.2.2 Dependance of performance by the configuration of MEIs

The results presented in this Section are devoted to show how the specific setting of the active links' MEIs impacts the performance in terms of possibility of activating further links. In partic-

Table 4.1: Example of 5 links activated by applying A-MEI.

step	M_1	M_2	M_3	M_4	M_5
a	1	∞	∞	∞	∞
b	0.78	0.78	∞	∞	∞
c	0.68	0.77	0.72	0.68	∞
d	0.37	0.76	0.71	0.67	0.37

Table 4.2: Example of 5 links activated by applying C-MEI.

step	M_1	M_2	M_3	M_4	M_5
a	1	∞	∞	∞	∞
b	0.74	1	∞	∞	∞
c	0.58	0.99	0.99	1	∞
d	**0**	0.98	0.98	0.98	0.71

ular, the aim is showing the behavior of the network as a function of the average level of MEIs and demonstrate that performance are improved by poorly sparse configurations of MEIs. As a consequence, these results confirm the advantages brought by access strategies that keep MEIs balanced.

In order to isolate the effect on performance of the configuration of MEIs, we simulated admissible topologies; thus, the distance of the achieved access probability from 1 is due only to the specific choice of MEIs. In particular, we generated a set of admissible topologies whose links' MEIs are set according to a gaussian distribution. In Figures 4.1, 4.2 and 4.3 the MEIs are all set to the same value, that is their variance is null.

Figure 4.1 is the plot of the achieved access probability as a function of the MEIs' level for different choices of the number of links N; the maximum power of the single device is P_{max}^{dv}=1 W. The main observation concerns the behavior of the access probability as a step function of the MEI level. Active links have to maintain enough MEI in order to permit the access to a new link. As we try to force a MEI level above the step point, the access probability saturates due to the existence of a maximum transmission power reflecting in an upper bound on the MEI actually acquirable. The saturation level of the access probability gets lower as the number of

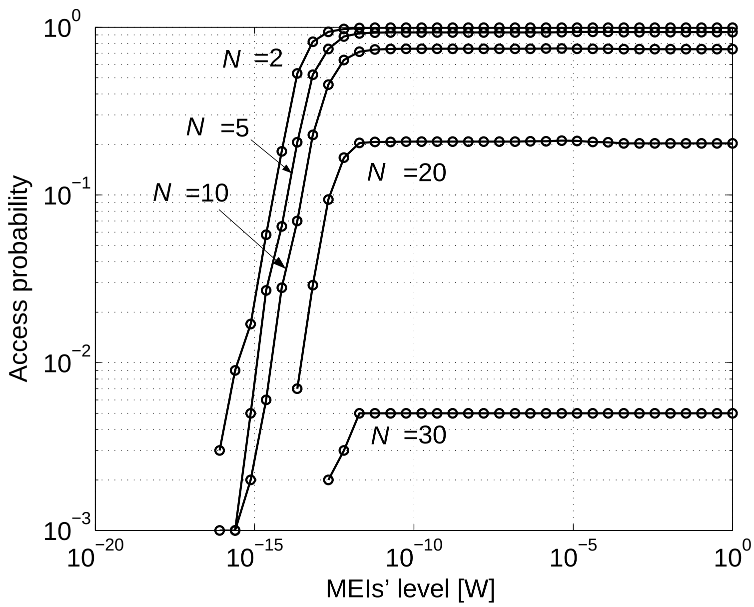

Figure 4.1: Access probability as a function of MEIs' common level for different values of N and $P^{dv}_{max} = 1\ W$.

active links increases due to the greater link density in the considered area.

We have also investigated the impact of the choice of P^{dv}_{max} on the curve of the access probability as a function of the MEIs' level. In particular, Figure 4.2 reports the two curves with N=10 links for the values P^{dv}_{max}=1 W and P^{dv}_{max}=∞ and shows that this impact is quite poor. In fact, it reflects just in a slight difference of the saturation value of the access probability for infinite MEIs' level. This behavior is highlighted also by the plot of the maximum and minimum transmission power levels obtained with the considered MEIs' configurations; Figure 4.3 refers to the four cases of P^{dv}_{max}=1 mW, 1 W, 10 W and ∞ with N=10 links. We can notice that the saturation value of P_{min} is proportional (just above 20%) to the saturation value P_{max} (which is P^{dv}_{max}).

Figure 4.4 reports the access probability obtained when the active links' MEI levels are set according to a fixed average value, equal to $10^{-6}\ W$ as indicated in the figure, and with a variable standard deviation for different values of the number N of links. The maximum power per device is P^{dv}_{max}= 1 W. This plot shows the interesting behavior that a MEI configuration with sparse MEI

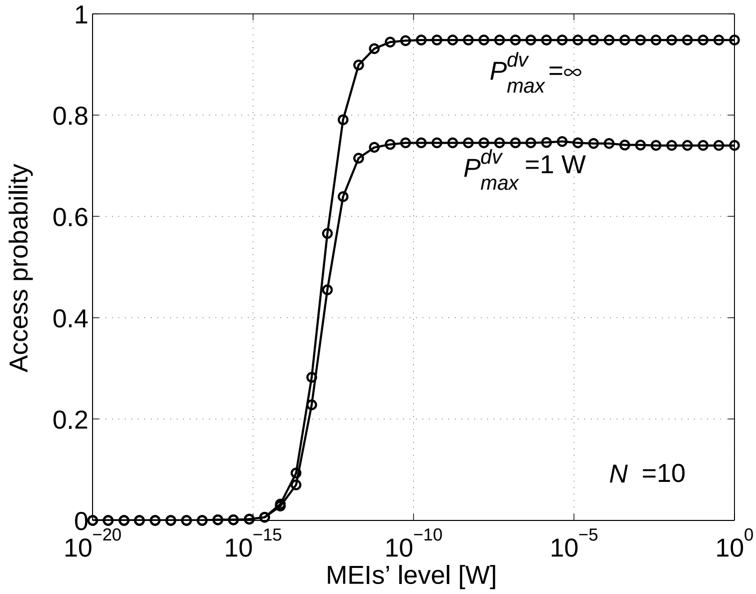

Figure 4.2: Access probability as a function of MEIs' common level for $N = 10$ and P^{dv}_{max}= $1\,W, \infty$.

levels degrades the access probability for new links; in particular the performance downgrading is as higher as the MEIs' standard deviation is greater. Thus, these results confirm that a margin based strategy aiming at balancing MEIs will outperform schemes which do not care of keeping MEIs balanced.

4.3 Probability of activating N links

A performance metric is the probability of successfully activating all the links of a given topology at the desired values of rate R and SIR γ^T. We derived this probability for the three access strategies defined in Section 4.1, that is A-MEI, C-MEI and MIN-P.

As for A-MEI and C-MEI, we first studied the impact on performance of the initial MEI, $M0$. Figure 4.5 reports the probability of activating N links as a function of $M0$ for different values of N. Both for A-MEI and C-MEI, initially the greater $M0$ the higher the probability of activating a number N of links. Then the A-MEI curves saturate due to the maximum power constraint

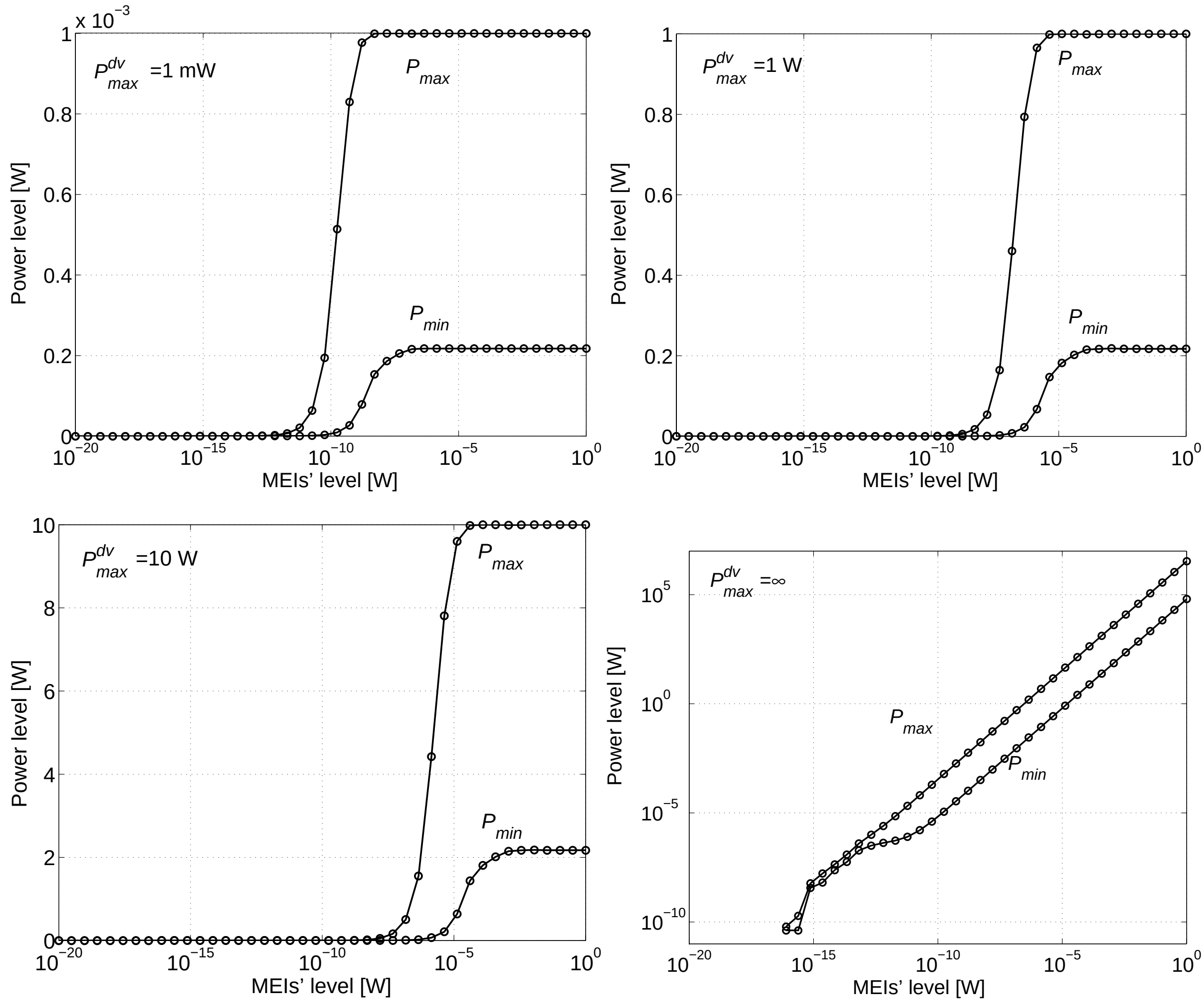

Figure 4.3: Maximum and minimum transmission power levels for N=10 and P_{max}^{dv}= 1 mW, 1 W, 10 W, ∞.

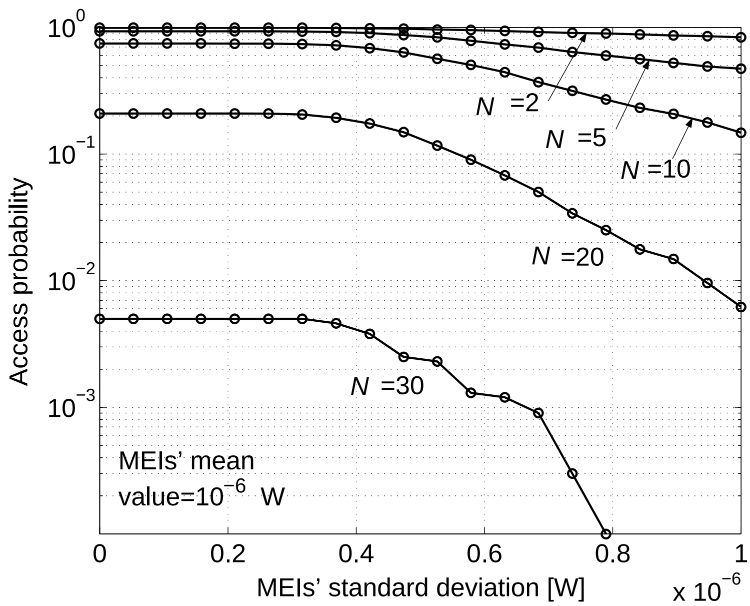

Figure 4.4: Access probability as a function of MEIs' standard deviation for different values of N, $P^{dv}_{max} = 1\ W$ and MEIs' mean value= $10^{-6}\ W$.

that limits also the actually achievable MEIs. Instead, as for C-MEI, the curves reach a peak and then decrease, tending to a constant value. In this case, since $M0$ represents the initial MEI that each new link tries to achieve, the entering links generate higher interference that future links will have to overcome with higher transmission powers thus quickly saturating the maximum power constraint. Figure 4.5 can also be interpreted as the access scheme behavior as a function of the MEI/power configuration indicating a possible criterion of reconfiguring powers in A-MEI during link lifetime. In fact, once identified the "elbow" of the curves, a reconfiguration process during the communication's lifetime could make the network move to the minimum level allowing to reach the saturation floor. Let us also notice that with N=2 links, the two access schemes perform the same way. In fact, the MEI acquired by the second link does not matter since further entering links are not considered. In general, a strategy of adaptive selection of MEIs becomes important as the number of links increases. Another interesting observation concerns the behavior for very low values of $M0$; in this case fixed MEIs show to perform better than adaptive ones in terms of access probability. This effect is due to the very poor probabilities

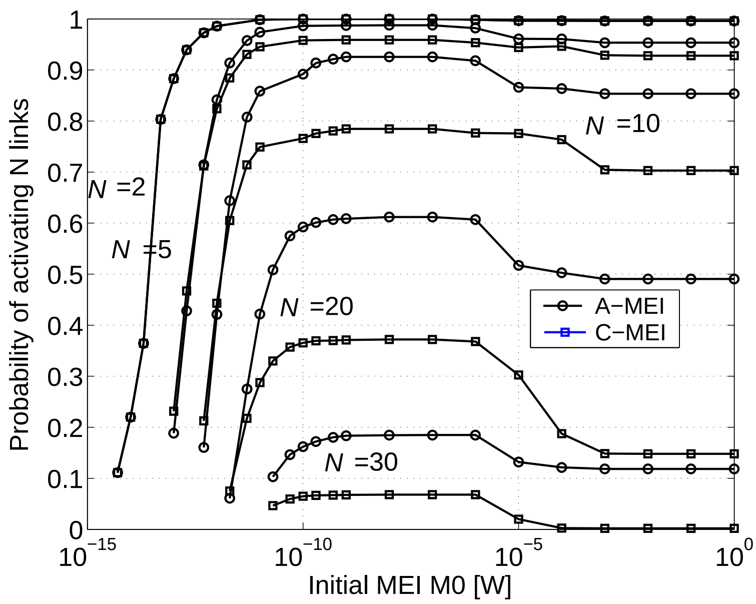

Figure 4.5: Probability of activating N links as a function of the initial MEI ($M0$) for different values of N.

of successfully accessing the channel and to the fact that fixed MEIs allow a higher average MEI thus resulting in better performance. When $M0$ increases, after a saturation floor, there is a slight degradation in performance since the high value of $M0$ forces links to saturate their transmission power thus achieving low MEIs. This degradation is more significative in case of C-MEI since the increasing $M0$ leads to configurations of MEIs more unbalanced.

Figure 4.6 represents a comparison of the proposed access strategy with the theoretical curve achievable by adopting a scheme reconfiguring continuously transmission powers at the Pareto-optimal solution (MIN-P), besides with the strategy C-MEI. As for the scheme MIN-P, we remind that by assumption it exhibits an ideal behavior by rejecting access requests that would force some links to reach the maximum power. In Figure 4.6 we show the probability of activating N links as a function of N; for A-MEI and C-MEI we adopted an initial MEI $M0$=10^{-6} W. The curve labelled as MIN-P shows the maximum access probability as a function of the number of links. A-MEI outperforms C-MEI and further improvements are expected by introducing a reconfiguration mechanism after each new access re-balancing the MEIs. In comparing A-MEI

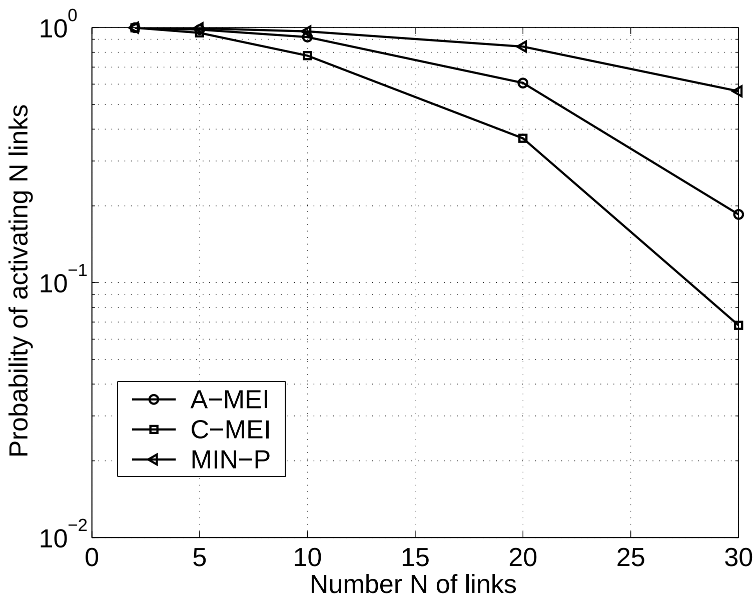

Figure 4.6: Probability of activating N links as a function of N for $M0$=10^{-6} W.

and C-MEI, we have to consider that both require the explicit signaling of MEIs among different links. Instead, as for the distributed implementation of MIN-P, we remind that, although solutions of implementation have been proposed based on measurements (e.g., see [44] and [48]), the bound on the device transmission power is completely neglected. This simplifying assumption deeply affects performance in real scenarios, while it becomes essential for employing technologies like UWB in unlicensed bands respecting regulatory body's masks.

4.4 Performance on throughput

As further performance metric for comparing A-MEI to C-MEI and MIN-P, we have taken into consideration the system throughput respectively achieved by the three schemes. In particular, here with throughput we mean the overall data rate allocated assuring the desired target SIR, that is the number of communications successfully admitted multiplied by the relevant (guaranteed) data rate. We adopted the value $M0$=10^{-6} W for the initial MEI in A-MEI and C-MEI. Specifically, Figure 4.7 shows the mean throughput as a function of the number N of links; also the

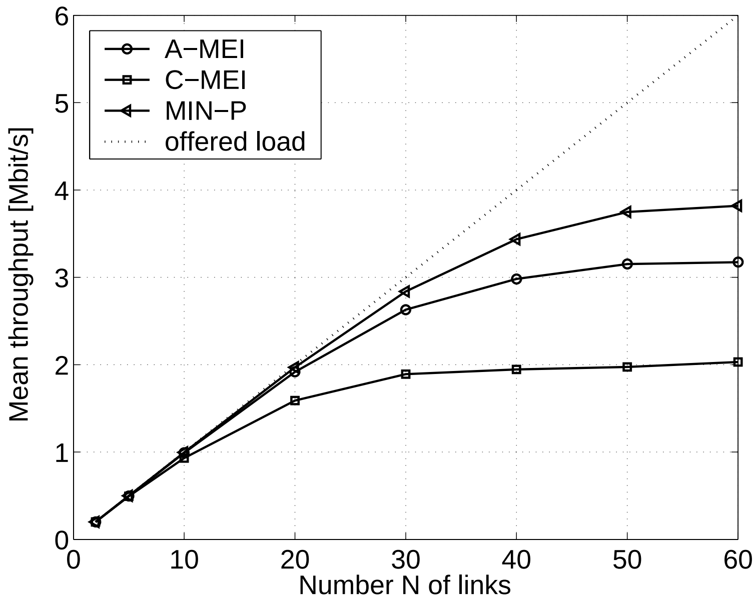

Figure 4.7: Mean throughput as a function of the number N of links ($M0$=10^{-6} W for A-MEI and C-MEI).

curve of the offered load is drawn (see the dotted line). As for Figures 4.8, 4.9 and 4.10, the considered topologies are constituted by N=60 links and the plots are the histograms of the measured percentage of occurrence of the overall throughput respectively in case of A-MEI, C-MEI and MIN-P.

These results highlight the better performance of A-MEI with respect to C-MEI in terms of achieved mean throughput. In particular A-MEI shows to reach values of the throughput not too much far away from the maximum ones of the ideal scheme MIN-P. The histogram of A-MEI (Figure 4.8) is centered around higher values of throughput with respect to C-MEI while with this latter strategy lower values of the mean throughput are more probable. These results are clearly in favor of a balanced MEI based strategy and could be further improved by means of power reconfigurations during the links' lifetime.

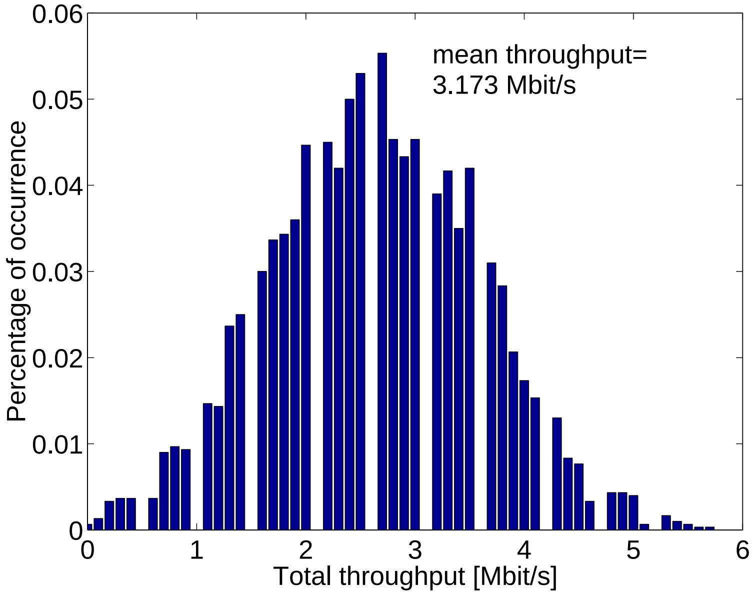

Figure 4.8: Percentage of occurrence of overall throughput values in case of A-MEI (N=60, $M0$=10^{-6} W).

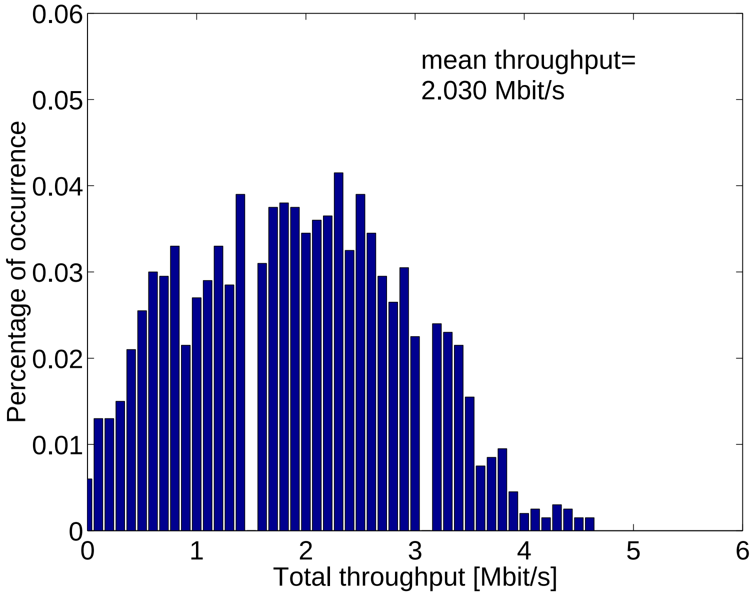

Figure 4.9: Percentage of occurrence of overall throughput values in case of C-MEI (N=60, $M0$=10^{-6} W).

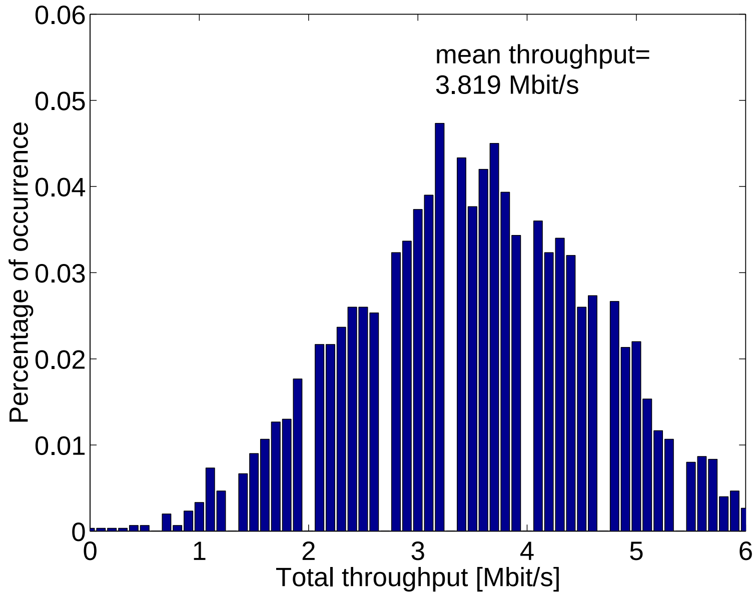

Figure 4.10: Percentage of occurrence of overall throughput values in case of MIN-P (N=60).

4.5 Results relevant to an UWB access network

The results presented in this Section have been derived simulating an air interface characterized by the employment of the UWB technology with the SIR expression in equation (3.3) and by a centralized topology with APs and RTs as considered in the WHYLESS.COM project. As for the UWB air interface, we set the relevant parameters at the following values: temperature noise in antenna of $300\ K$ plus a receiver noise figure of $10\ dB$, thus equivalent noise temperature T such that $kT = -194\ dBW/Hz$, $E_W = 1.08 \cdot 10^{-10}\ s$, $m_p = 1.7464 \cdot 10^{-10}\ s$ and $\eta_\circ = 2.462 \cdot 10^{-20}\ W/Hz$ (i.e., $-196.09\ dBW/Hz$). The path gain is assumed to be a function of the link extension d according to the formula $g = (\frac{\lambda}{4\pi d})^2$ with $\lambda = \frac{c}{f_c}$ and assuming $f_c = 1\ GHz$.

We simulated the specific topology represented in Figure 4.11 where two fixed APs — denoted by AP1 and AP2 — provide the UWB access to a number of RTs in an area of $100m \times 50m$. The links between the RTs and their serving AP are full-duplex with link rate R=1 $Mbit/s$ and target SIR γ^T=5. We assume that the forward and reverse links of a radio device do not interfere

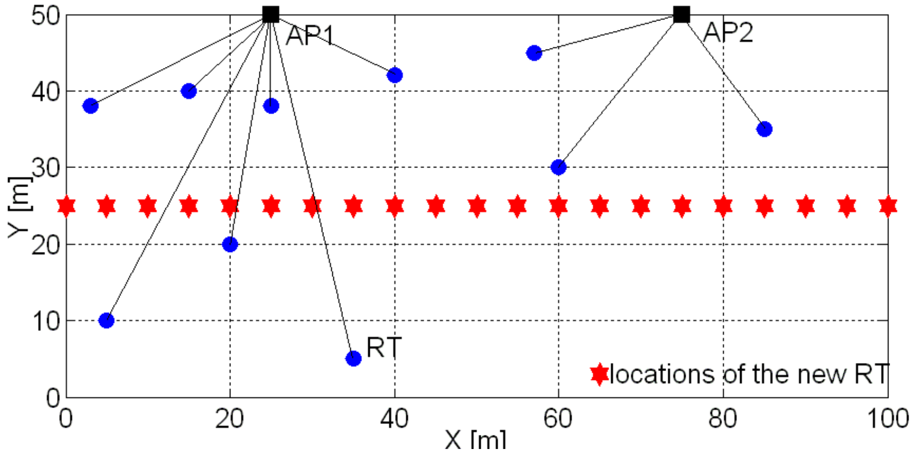

Figure 4.11: Considered topology (with indication of the new RT's locations).

each other. We consider a maximum power level allowed for a single device compliant with FCC's masks ([54]) and equal to P_{max}=0.5 mW.

Ten links are already active and a new one should be activated between a new RT entering the system and either AP1 or AP2. The MEIs of the active links before the new access are randomly distributed in a range of values centered in $5 \cdot 10^{-12}$ W and wide the 10% of the central value, i.e., $0.5 \cdot 10^{-12}$ W. In Figure 4.11 gray dots indicate the considered possible locations of the new RT which are distributed in a straight line at steps of 5 m. As a function of the 21 possible locations and for both APs, we computed the minimum, maximum and optimal transmission powers that can be used by the new RT and the maximum rate that can be sustained in both uplink and downlink. Figures 4.12 and 4.13 report the transmission power levels respectively for uplink and downlink. In these two figures the apex refers to the radio entity acting as transmitter — the RT in uplink and the AP in downlink; moreover, the apex RT(1) stands for the uplink toward AP1 while RT(2) for the one toward AP2. As for the uplink maximum transmission power, the used apex does not specific the AP since this quantity depends only on the RT. Figures 4.14 and 4.15 concern the achievable rate respectively in uplink and downlink.

The power levels' curves (Figure 4.12 and 4.13) put in evidence the non admissible locations of the new link for either AP1 or AP2 due to a level of the minimum transmission power

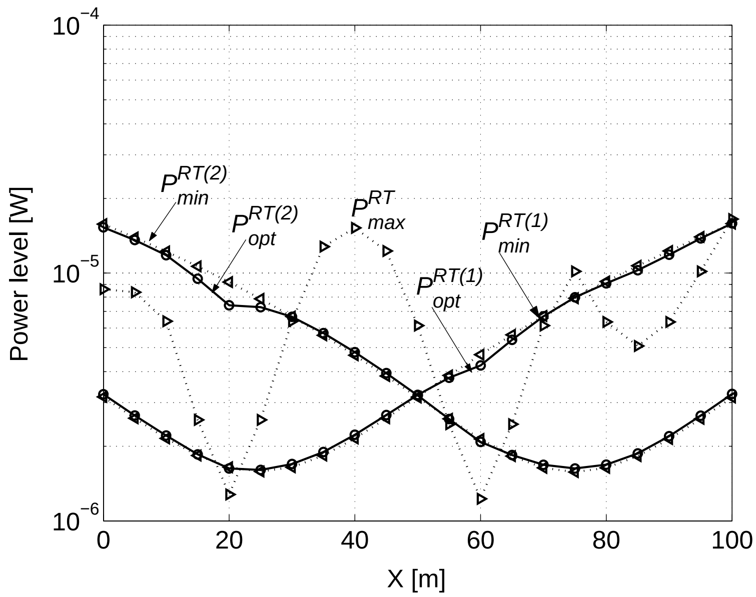

Figure 4.12: Uplink power levels as a function of the new RT's location.

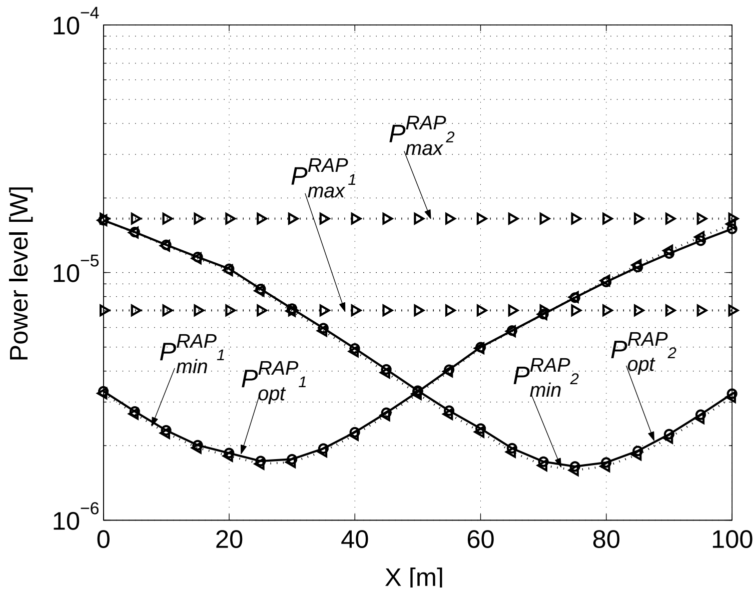

Figure 4.13: Downlink power levels as a function of the new RT's location.

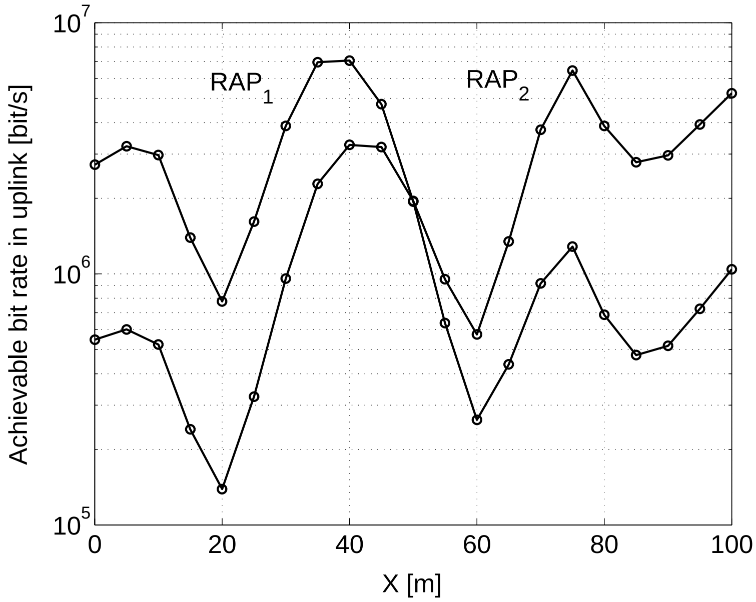

Figure 4.14: Uplink sustainable rates as a function of the new RT's location.

above the maximum one. For instance, when the new RT is placed in the locations with either X=$0 \div 30\ m$ or X around $60\ m$, the relevant uplink can not be established at the desired QoS parameters of R=1 Mbit/s and γ^T=5 with AP2; nevertheless, the maximum sustainable rate by this AP in uplink is positive and less than $1\ Mbit/s$, as indicated in Figure 4.14. Similarly in the downlink with AP1 for the RT's locations with X=$70 \div 100\ m$, where the RT can achieve a rate less than $1\ Mbit/s$ maintaining γ^T=5, as indicated in Figure 4.15.

The curves in Figures 4.14 and 4.15 also indicate the most convenient AP for each possible location of the new RT in terms of bit rate respectively for the uplink and the downlink. Specifically, an interesting observation concerns the downlink. First, let us remind that the value of the maximum sustainable rate depends on the maximum transmission power, the interference level and the path gain. In correspondence of the locations with X=$40 \div 50m$, the AP offering the higher bit rate is AP2, even if it is not the closest AP to the RT, thanks to the better overall conditions in its coverage area, particularly in terms of MEIs' levels resulting in a higher maximum power in respect of AP1.

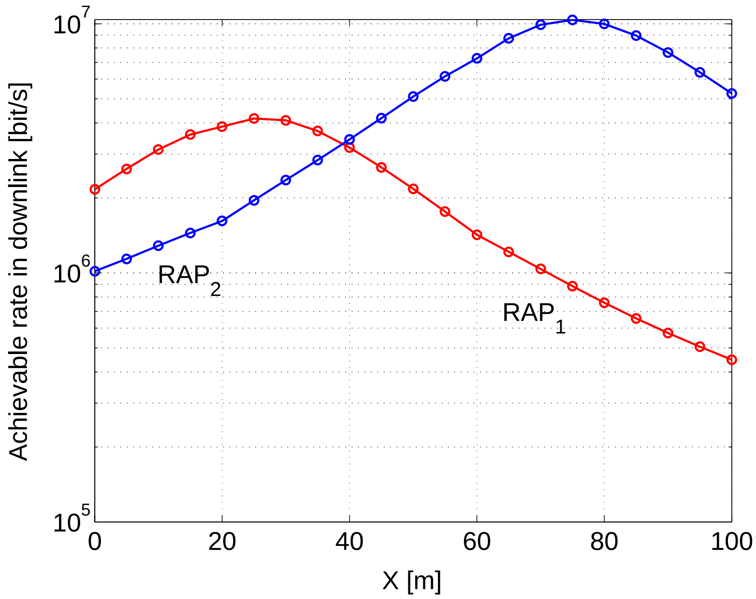

Figure 4.15: Downlink sustainable rates as a function of the new RT's location.

Conclusions

In this thesis we deal with the problem of radio resource control and, in particular, of the admission control in distributed radio systems. The methodology we adopt is based on introducing power management as RRC procedure jointly handled with measurements of the environment according to a cross-layer philosophy of network design. The specific goal is defining a scheme able to support differentiated levels of quality of service.

The result is an innovative scheme of distributed radio resource control based on power regulation. The three functions of QoS description, admission control and resource allocation are defined facing the RRC problem in a complete way within the framework of ad-hoc networks, differently from other works in literature which just define the only access rule ([52]) or a probing procedure for the access ([48]) or a power control algorithm ([44]). In this thesis we faced the following issues:

- formalization of the problem of power controlled radio resource control with specific care of the access rule;
- identification of the possible solutions to the problem;
- selection of a specific solution according to the criterion of trading off effectiveness for a simple implementation;
- definition of the relevant implementation.

A performance study has been carried out with the aim of highlighting the differences between the two main methodologies of radio resource control with power regulation currently considered and investigated in the research world, that is:

1. strategies continuously adapting transmission power levels on the basis of a distributed algorithm with the only aid of measurements of the environment;

2. strategies employing both measurements and signaling exchange — performed according to a peer-to-peer communication model — to calculate transmission power levels at the access.

It has been widely discussed that the first group of schemes generally outperforms the second but presents problems of robustness in the maintenance of the negotiated QoS level while the second group of schemes loses some performance being more robust. Our proposal, which belongs to this latter group, introduces a smart algorithm of power selection at the access in order to recover some performance still assuring the same robustness.

The proposed scheme of radio resource control has been applied to the network context of the IST WHYLESS.COM project where UWB is employed as access technology. Here, the considered architecture is not properly ad-hoc, nevertheless the radio segment behaves in accordance to a distributed model with control of the radio resource according to a peer-to-peer paradigm. The result is *i*) introducing a deal of flexibility in the managing of the UWB radio resource making possible a simple coexistence among accesses to the fixed network and their services and ad-hoc links supporting local communications as well as *ii*) avoiding a rigid resource planning as in cellular systems. Within the WHYLESS.COM architecture the employed strategy is also applied as means of evaluation of the available resource, besides admission control.

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List of papers

The following is the comprehensive list of the papers (co)authored by Cristina Martello dealing with the research topic of this thesis.

1. N. Blefari Melazzi, F. Cuomo, M. Femminella and *C. Martello*, ”Integrating UWB Radio Access Procedures with a Stateless IP QoS Paradigm”, **Proceedings of IEEE Vehicular Technology Conference Fall 2003**, Orlando (Florida), October 6-9, 2003.

2. F. Cuomo and *C. Martello*, ”A Distributed Power Regulated Algorithm Based on SIR Margins for Adaptive QoS Support in Wireless Networks”, **Proceedings of Personal Wireless Communications 2003**, Venezia (Italia), September 23-25, 2003, vol. 2775 of LNCS, pp. 114-127.

3. F. Cuomo, *C. Martello* and S. Caputo, ”An Interference-Controlled Admission Control Scheme for QoS Support in Distributed UWB Networks”, **Proceedings of IST Mobile Communications Summit 2003**, Aveiro (Portugal), June 15-18, 2003, pp. 508-512.

4. F. Cuomo, *C. Martello*, A. Baiocchi and F. Capriotti, ”Radio Resource Sharing for Ad-Hoc Networking with UWB”, Special Issue ”Ultra Wide Band Radio in Multi-Access Wireless” of **IEEE Journal on Selected Areas in Communications**, vol. 20, no. 9, December 2002, pp. 1722-1732.

5. F. Cuomo, A. Baiocchi, F. Capriotti and *C. Martello*, ”Radio Resource Optimisation in an UWB Wireless Access”, **Proceedings of IST Mobile Communications Summit 2002**, Thessaloniki (Greece), June 17-19, 2002, pp. 723-727.

6. *C. Martello* and D. Bocchetta, ”Power Controlled MAC Protocols for Wireless Ad-Hoc Networks”, **Proceedings of European Wireless 2002**, Firenze (Italia), February 26-28, 2002, pp. 319-326.

7. *C. Martello*, ”UWB Radio Resource Control: MAC Functional Model and Resource Sharing Approach”, **Proceedings of the First International Workshop Networking with UWB**, ed. Ingegneria 2000, Roma (Italia), December 21, 2001.

8. F. Cuomo and *C. Martello*, ”MAC Principles for an Ultra Wide Band Wireless Access”, **Proceedings of IEEE GLOBECOM 2001**, San Antonio (Texas), pp. 3548-3552, November 25-29, 2001.

9. A. Baiocchi, F. Capriotti, F. Cuomo and *C. Martello*, ”Distributed Radio Resource Sharing with UWB”, **Proceedings of IST Mobile Communications Summit 2001**, Barcelona (Spain), September 9-12, 2001, pp. 753-758.

The other papers published during the Ph.D. course (co)authored by Cristina Martello are listed below.

10. A. Baiocchi, F. Cuomo and *C. Martello*, ”Optimizing the Radio Resource Utilization of Multiaccess Systems with a Traffic-Transmission Quality Adaptive Packet Scheduling”, **Computer Networks** (ed. Elsevier), vol. 38, no. 2, February 5, 2002, pp. 225-246.

11. A. Baiocchi, F. Cuomo and *C. Martello*, ”Joint Channel and Traffic Adaptive Packet Scheduling over Multiaccess Radio Interfaces”, **Proceedings of IEEE ICC 2001**, Helsinki (Finland), June 11-14, 2001, pp. 2872-2876.

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List of Acronyms

ACK Acknowledgment

ACL Asynchronous Connection-Less

AC-phase Admission Control phase

AD Administrative Domain

ANR Access Network Router

AP Access Point

ARQ Automatic Repeat Request

ASP Application Service Provider

BAN Body Area Network

BER Bit Error Rate

BI Backoff Interval

CDMA Code Division Multiple Access

CR Core Router

CSMA/CA Carrier Sense Multiple Access/Collision Avoidance

CTS Clear-To-Send

CW Contention Window

DCF Distributed Coordination Function

DIFS Distributed inter-Frame Space

EDCF Enhanced Distributed Coordination Function

ER Edge Router

FDMA Frequency Division Multiplexing

FHSS Frequency Hopping Spread Spectrum

HCF Hybrid Coordination Function

HC Hybrid Coordinator

ID-phase Identification phase

IFS Inter-Frame Space

IP Internet Protocol

ISM Industrial Scientific Medical

LAN Local Area Network

MAC Medium Access Control

MEI Maximum Extra Interference

NRB Network Resource Broker

NRM Network Resource Manager

OFDM Orthogonal Frequency Division Multiplexing

OSI Open System Interconnection

PAN Personal Area Network

PCF Point Coordination Function

PC-RRC Power Controlled Radio Resource Control

PDA Personal Digital Assistant

PDB Per Domain Behavior

PPM Pulse Position Modulation

QoS Quality of Service

RRC Radio Resource Control

RT Radio Terminal

RTS Request-To-Send

SCO Synchronous Connection Oriented

SIFS Short Inter-Frame Space

SIG Special Interest Group

SIR Signal-to-Interference-Ratio

TDD Time Division Duplex

TDMA Time Division Multiplexing

TH Time Hopping

UWB Ultra Wide Band

WAD Wireless Administrative Domain

WAN Wide Area Network

WLAN Wireless Local Area Network

Contents

Enclosed papers (co)authored by Cristina Martello