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Cross-layer Resource Allocation for MB-OFDM UWB Systems

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1. Introduction

The demand of wireless services is increasing and new generations of mobile radio systems are promising to provide higher data rates and a large variety of applications to mobile users. Besides, one of the major challenging problems in future wireless communication systems is how to offer the ability to transport multimedia services at different channel conditions and bandwidth capacities with various quality of service (QoS) requirements. However, this goal must be achieved under the constraint of limited available frequency spectrum because numerous licensed services and applications already exploit the spectral resource up to several gigahertz. Thereby, the multiple access and the coexistence are challenging matters for the next generation wireless communication systems.

Two exciting solutions have recently risen to circumvent the limited frequency spectrum problem. The first solution is based on spectrum sensing and dynamic spectrum access (DSA) techniques to find available spectrum which can be used by a cognitive radio user without causing any harmful interference to licensed users. The other solution is to set up underlay communications that would allow so-called secondary users to judiciously exploit some frequency resource already allocated to licensed primary users such that the former does not impact on the quality of the communications of the latter significantly. The latter solution can namely be achieved by imposing tough radiation restrictions to the secondary users.

In that context, ultra-wideband (UWB) has recently been attracting great interest as a suitable technology for unlicensed short range communications. With the data rate of several hundred Mbps, and the restricted power transmission, UWB demonstrates great potential in the coexistence issue and the support of multimedia services such as high-definition television (HDTV), videos and music sharing, console gaming, etc., in home networks known as the wireless personal area network (WPAN).

Given the power constraint and the extremely wide bandwidth of UWB, a fundamental problem arises is how to manage the multiple-user access to efficiently utilize the bandwidth, support the QoS requirements of multimedia applications and provide fairness among the existing users. Moreover, to this date, research works on resource allocation for UWB communications are still limited. Based on the WiMedia Alliance, solution proposed for the UWB communications, the objective of this chapter is to define a new approach for the spectrum sharing and multiple access problems in the scope of the resource allocation in UWB systems while taking into account the various system constraints. Thus, to deal with the channel quality, and the QoS constraints, which are viewed as heterogeneous constraints, we follow a cross-layer approach based on a cooperation between the two lowest layers of the Open Systems Interconnection (OSI) model, namely the physical (PHY) and the medium access control (MAC) layers.

This chapter is divided into two main parts: In the first part, we describe the multiband orthogonal frequency-division multiplexing (MB-OFDM) approach, solution proposed for the high-rate UWB systems. Next, we present the physical specifications of the WiMedia solution, which is based on the MB-OFDM approach. The indoor channel model that will be used in our simulations is then presented. Afterwards, we present the resource management principles in OFDM and MB-OFDM systems. We then discuss the resource allocation strategies proposed for OFDM systems while stressing on the need of the QoS support in a multiuser context to respond to the different users demands. Finally, we define our cross-layer strategy for a distributed multiuser resource allocation scheme under QoS requirements in MB-OFDM systems.

Based on the cross-layer approach defined in the first part, we analytically study in the second part of the chapter the multiuser resource allocation problem for MB-OFDM systems by deriving a constrained optimization problem. The cross-layer approach is exploited by defining a PHY-MAC interplay mechanism that is able to provide new functionalities of the physical and the medium access control layers. The PHY layer is responsible for providing the physical channel conditions through the exploitation of the channel state information (CSI), while the MAC layer is in charge of differentiating and classifying the existing users using a priority-based approach that guarantees a high level of QoS support for real-time and multimedia services. An optimal sub-band and power allocation is then derived from the formulated cross-layer optimization problem. To evaluate the efficiency of the proposed multiuser allocation scheme, we define a cross-layer metric called the satisfaction index (SI). Finally, the new multiuser resource allocation solution is compared to the single-user WiMedia solution in terms of bit error rate (BER).

2. MB-OFDM system

Multiband OFDM (MB-OFDM) is the primary candidate for high data rate UWB applications. It was first proposed by Anuj Batra *et al.* from Texas Instruments for the IEEE 802.15.3a task group (Batra et al., 2003, 2004a, 2004b). This approach is today supported by the WiMedia Alliance and adopted by the ECMA-368 standard (Standard ECMA-368, 2007).

Data rate (Mbps)	Constellation	Coding rate (r)	FDS	TDS	Coded bits / OFDM symbol (NCBPS)
53.3	QPSK	1/3	Yes	Yes	100
80	QPSK	1/2	Yes	Yes	100
110	QPSK	1/3	No	Yes	200
160	QPSK	1/2	No	Yes	200
200	QPSK	5/8	No	Yes	200
320	DCM	1/2	No	No	200
400	DCM	5/8	No	No	200
480	DCM	3/4	No	No	200

Table 1. WiMedia-based MB-OFDM data rates.

The WiMedia Alliance MB-OFDM scheme consists in combining OFDM with a multi-banding technique that divides the available band into 14 sub-bands of 528 MHz each, as illustrated in Fig. 1. An OFDM modulation with 128 subcarriers is applied on each sub-band separately. As evident from the figure, five band groups or channels are defined, each being made from three consecutive sub-bands, except for the fifth one which encompasses only the last two sub-bands. To be exhaustive, a sixth band group is also defined within the spectrum of the first four, consistent with usage within worldwide spectrum regulations. A WiMedia compatible device should actually make use of only one out of these six defined channels. Initially, most of the studies in the literature have been performed on the first band group from 3.1 to 4.8 GHz.
The MB-OFDM system is capable of transmitting information at different data rates varying from 53.3 to 480 Mbps, listed in Table 1. These data rates are obtained through the use of different convolutional coding rates, frequency-domain spreading (FDS) and time-domain spreading (TDS) techniques. FDS consists in transmitting each complex symbol and its conjugate symmetric within the same OFDM symbol. It is used for the modes with data rates of 53.3 and 80 Mbps. With the TDS, the same information is transmitted during two consecutive OFDM symbols using a time-spreading factor of 2. It is applied to the modes with data rates between 53.3 and 200 Mbps.
For data rates lower than 320 Mbps, the constellation applied to the different subcarriers is a quadrature phase-shift keying (QPSK). Nevertheless, for data rates of 320 Mbps and higher, the binary data is mapped onto a multi-dimensional constellation using a dual-carrier modulation (DCM) technique. The DCM modulation consists in mapping four bits onto two 16-point constellations. The resulting mapped tones are then separated by at least 200 MHz of bandwidth. The DCM technique is not applied for low data rates (200 Mbps and below) since the frequency diversity is better exploited through the use of low rate Forward Error Correction (FEC) codes, TDS and FDS techniques. Therefore, the expected DCM diversity gain for these data rates is minimal and the added complexity for DCM is not justified. Note that the first MB-OFDM proposals for IEEE 802.15.3a, including the September 2004 proposal, considered only a QPSK constellation for all the data rates (Batra et al., 2004b).

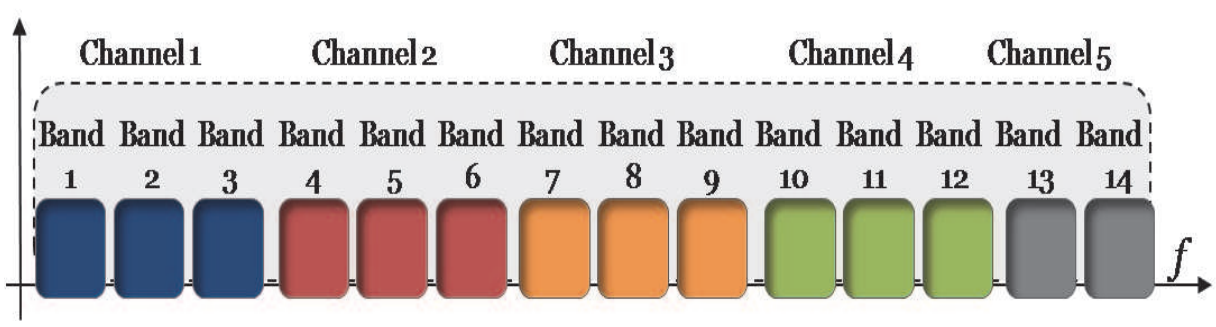

Fig. 1. UWB spectrum bands in the MB-OFDM system.

2.1 UWB indoor channel model

Since UWB channels have some particular propagation process and models which carry a considerable difference with the classical narrowband models, many studies on the propagation and the channel models for UWB signaling have been issued since the late 1990s (Cassioli et al., 2002) (Win & Sholtz, 2002).

In fact, since we are working in an indoor environment and due to the very fine resolution of UWB waveforms, different objects or walls in a room could contribute to different clusters of multipath components. In early 2003, the IEEE 802.15.3a committee adopted a new UWB channel model for the evaluation of UWB physical layer proposals (Foerster, 2003). This model is a modified version of Saleh-Valenzuela (SV) model for indoor channels (Saleh & Valenzuela, 1987), fitting the properties of UWB channels. A log-normal distribution is used for the multipath gain magnitude. In addition, independent fading is assumed for each cluster and each ray within the cluster. The impulse response of the multipath model is given by

$$h_i(t) = G_i \sum_{z=0}^{Z_i} \sum_{p=0}^{P_i} \alpha_i(z,p)\delta\big(t - T_i(z) - \tau_i(z,p)\big) \quad (1)$$

where G_i is the log-normal shadowing of channel realization i, $T_i(z)$ the delay of cluster z, $\alpha_i(z,p)$ and $\tau_i(z,p)$ represent the gain and the delay of multipath p within cluster z, respectively. Independent fading is assumed for each cluster and each ray within the cluster. The cluster and path arrival times can be modeled as Poisson random variables. The path amplitude follows a log-normal distribution, whereas the path phase is a uniform random variable over $[0, 2\pi]$. Four different channel models (CM1 to CM4) are defined for the UWB system modelling, each with arrival rates and decay factors chosen to match different usage scenarios and to fit line-of-sight (LOS) and non-line-of-sight (NLOS) cases. The channel models characteristics are presented in Table 2.

3. Resource allocation in OFDM systems

OFDMA has attracted great interest as a promising approach to provide an efficient modulation and multiple-access technique for future wireless communications (Astely et al., 2006) (Moon et al., 2006). It is based on OFDM modulation, which is characterized by its immunity to intersymbol interference (ISI), its robustness in presence of frequency selective

	CM1	CM2	CM3	CM4
Mean excess delay (ns)	5.05	10.38	14.18	–
Delay spread (ns)	5.28	8.03	14.28	25
Distance (m)	< 4	< 4	4–10	10
LOS/NLOS	LOS	NLOS	NLOS	NLOS

Table 2. Multipath channel characteristics.

fading and narrowband interference and its high spectral efficiency. Besides, the major advantage of OFDMA is its ability to schedule resources in both time and frequency dimensions which gives a good flexibility in any multiple-access scheme. However, the performance of OFDMA depends on the ability to provide an efficient and flexible resource allocation scheme that should adapt to wireless fading channels, as well as improve the spectrum efficiency and satisfy the existing users.

In OFDM, the broadband channel is divided into orthogonal narrowband subcarriers. In a multiuser context, different subcarriers can be allocated to different users. However, the channels on each subcarrier are independent for each user; the subcarriers that experience deep fading for one user could be in a good condition for another user. Consequently, efficient resource allocation in OFDMA shall be based on dynamic subcarrier allocation that responds to each user channel quality.

In the literature, related studies have addressed the OFDM radio resource allocation problem as an optimization problem where optimal and suboptimal algorithms have been proposed. Two well-known classes of optimization techniques have been proposed for the dynamic multiuser OFDM allocation: margin adaptive (MA) and rate adaptive (RA). The MA concept is to achieve the minimum overall transmit power under a data rate or BER constraint. On the other hand, the RA concept is to maximize the users data rate under a total transmit power constraint (Jang & Lee, 2003) (Shen et al., 2005).

3.1 Resource allocation in MB-OFDM UWB systems

UWB channel response varies slowly in time and could be considered as quasi-static during one frame. Accordingly, the CSI can be sent to the transmitter by a simple feedback that does not increase significantly the complexity of the resource allocation mechanism. However, to this date, research works on resource allocation for UWB communications are still limited.

Several research studies on MB-OFDM UWB systems have been strictly devoted to physical layer issues or have addressed the question of resource allocation yet without taking into consideration the MAC layer constraints. In (Chen et al., 2006) for instance, in order to improve the BER performance, an adaptive carrier selection and power allocation is proposed. An optimal algorithm with Lagrange multiplier method is derived. Based on the CSI information, the carriers and the power are dynamically allocated with the constraint of fixed data rate and fixed total power. In (Wang et al., 2005), the authors propose two power allocation schemes to maximize the total capacity for single-band OFDM UWB transmissions with space-time codes, under the assumption of perfect and partial CSI at the transmitter. The results show that the water-filling scheme provides the smallest outage probability while the scheme with limited CSI feedback has lower feedback overhead and slight performance loss. In (Xu & Liu, 2004), a power allocation scheme is proposed for clustered MB-OFDM. In this study, a cluster which is a group of subcarriers is dynamically assigned a unique power in order to maximize the total system throughput. The results show that the proposed solution, with its low complexity, has a performance close to the one of a standard water-filling scheme.

On the other hand, other studies have been focusing on improved MAC algorithms independently of any information feedback from the PHY layer. In (Cuomo et al., 2002), a joint rate and power assignment algorithm is proposed for multiuser UWB networks. Optimal and suboptimal algorithms are proposed to dynamically assign the rate and the transmitted power of each node. To establish a communication link, the proposed radio resource sharing scheme defines a handshaking stage between a sender and receiver. The proposed allocation scheme relies on two handshakes between the sender and its neighbors to obtain the required information for link rate and power assignments. In (Zhai, 2008), a QoS support mechanism for multimedia services in UWB-based WiMedia mesh networks is proposed. An integer-linear programming model is derived to solve the path available bandwidth problem. Lower and upper bounds are also derived to reduce the computation complexity. In addition, a distributed QoS routing algorithm is defined to find the paths with enough end-to-end available bandwidth. Results show that the proposed algorithms perform very well in predicting the available bandwidth of paths and can admit more traffic flows than existing ones.

Few studies consider both the physical and MAC layers in the resource allocation matter for MB-OFDM UWB systems. In (Siriwongpairat et al., 2007), a novel channel allocation scheme is proposed by efficiently allocating power, data rate and sub-bands among all the users. The sub-band and power assignment problem is formulated as an optimization problem whose goal is to minimize the total power under the condition that all users achieve their requested data rates. A low-complexity fast suboptimal algorithm is also proposed to reduce the complexity of the formulated problem. Results show that the proposed solution can save up to 61% of power consumption compared to the standard multiband scheme. Although this latter study exploits information laying in the physical and MAC layers, some aspects are not ensured in the proposed resource allocation scheme. The QoS support for instance is not fully exploited since no service differentiation scheme is defined. Furthermore, some physical conditions are not taken into consideration in the sub-band assignment such as the number of sub-bands per channel and the number of users that can coexist in the same channel.

3.2 Resource allocation for MB-OFDM-MA: cross-layer approach

While OFDMA is the multiuser OFDM scheme that allows multiple access on the same channel by distributing subcarriers among users, MB-OFDM-MA is the multiuser MB-OFDM scheme that shares the available sub-bands of the same channel among the existing users.

Inevitably, there is a need in any resource allocation scheme to exploit some channel parameters reflecting the channel quality of each user aiming at accessing the network. These physical conditions are provided by the PHY layer. On the other hand, in a multiuser context, we need to determine how much end-users are satisfied and how efficient the available resources are shared among the existing users. Information about QoS requirements and fairness are thus of great importance to be provided by the MAC layer. As a result, the interplay between the two lowest layers of OSI model becomes a crucial need for the resource allocation in the next generation wireless communication systems since independent optimization of the two layers may not lead to an optimal overall system performance. Fig. 2 illustrates the idea of the PHY-MAC interaction model for a cross-layer optimization resource allocation scheme.

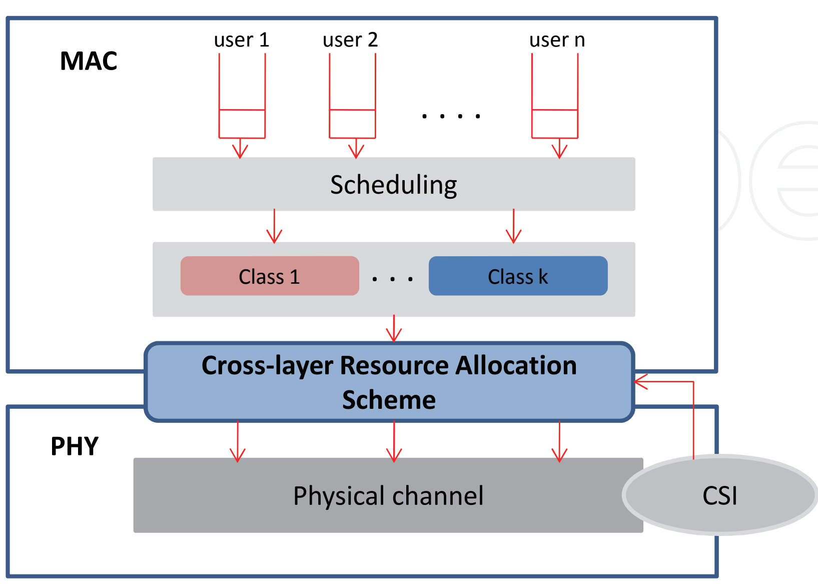

Fig. 2. PHY-MAC interaction for a cross-layer resource allocation scheme.

3.2 Cross-layer performance optimization

The management of the available resources is of major importance in a multiuser system when we want to optimize its performance. In our proposed cross-layer system that takes into consideration two different layers aspects, we should ensure an efficient exploitation of the available optimization features.

From the physical perspective, metrics such as spectrum efficiency and minimum BER are the most important constraints to be considered. On the other hand, from a user perspective, QoS as well as fairness among the competing users are the main metrics because they determine how much end-users are satisfied and how efficient the available resources are shared among the existing users. The optimization of the joint consideration of the PHY and MAC layers through the proposed cross-layer mechanism is thus performed by adopting two strategies:

Optimization problem formulation

The proposed cross-layer resource allocation problem is first studied analytically by deriving a constrained optimization problem to find the optimal allocation solution. Indeed, different parameters from the PHY and MAC layers are collected to define the objective function and the different constraints of the optimization problem.

Layer abstraction

To reduce the overall processing and the complexity of the layer-independent performance evaluation, an abstraction of one layer processing is carried out in the other layer. More precisely, all the proposed MAC processes will be abstracted at the PHY level for the sake of a simplified system performance evaluation.

4. Multiuser resource allocation optimization for MB-OFDM UWB

The proposed multiuser allocation scheme counts on the collection of information located at two different levels, more precisely the PHY and the MAC levels. In this section, we present the new functionalities of these two layers that should contribute to the optimization problem formulation.

4.1 PHY layer information

As mentioned before, the main functionality of the PHY layer is to provide the users channel gains of each sub-band in order to achieve efficient spectrum utilization and a sub-band allocation that respects the competing users PHY conditions. Therefore, the CSI is needed at the transmitter side.

In an OFDM system, by assuming a normalized emission power, we can derive the instantaneous signal to interference and noise ratio (SINR) for each subcarrier given by

$$SINR_i = \frac{|h_i|^2}{\sigma^2} \tag{2}$$

where h_i is the channel response of subcarrier i, $|h_i|^2$ and σ^2 are the subcarrier power and the noise and interference power respectively.

On the other hand, in a multiuser environment, it is desirable to evaluate the system level performance in terms of BER, considered as the physical QoS parameter. This can be motivated by the need of such parameter for accurate and realistic evaluation of the system

level performance but also for suitable development of adaptive resource allocation and packet scheduling algorithms. However, the heavy computation cost of any simulator assessing the system performance in terms of BER would result in long simulation times.
Therefore, separate link and system simulators are needed for the evaluation of the network performance. For this purpose, link to system (L2S) methods have been proposed in recent 3GPP standardizations, which can be effectively be used in OFDM systems by using effective SNR concept (3GPP, 2003a, 2003b).
The basic idea of the effective SINR method is to find a compression function that maps the sequence of varying SINRs to a single value that is correlated with the BER. This can be stated as

$$SINR_{eff} = I^{-1}\left(\frac{1}{N}\sum_{i=1}^{N} I(SINR_i)\right) \tag{3}$$

where *I(x)* is called the information measure function and N the number of subcarriers in a sub-band. An approach used for the effective SINR mapping method is called the Exponential Effective SINR Mapping (EESM) (3GPP, 2004a, 2004b).EESM uses the following information measure

$$I(x) = \exp(-\frac{x}{\lambda}) \tag{4}$$

The inverse function of I(x) is

$$I^{-1}(x) = -\lambda \ln(x) \tag{5}$$

Eventually, the effective SINR writes

$$SINR_{eff} = -\lambda \ln\left[\frac{1}{N}\sum_{i=1}^{N} \exp(-\frac{SINR_i}{\lambda})\right] \tag{6}$$

where λ is a scaling factor that is used to adjust the compression function in a way that compensates the difference between the actual BER and the predicted BER. λ depends only on the selected modulation and coding scheme (MCS).
In order to apply the effective SINR mapping method to MB-OFDM systems, we evaluate the value of λ for the eight data rate modes of the WiMedia system defined in Table 1. These values are listed in Table 3. In practice, based on the CSI knowledge, each user is capable of computing the effective SINR value in each sub-band by using (6). For instance, in the case of one channel divided into $N = 3$ sub-bands, and with $K = 3$ users, the physical layer information is reduced to the knowledge of only $N \times K = 9$ effective SINR values.

4.2 MAC layer information

In a multiuser context, the MAC layer is responsible for providing medium access mechanisms that should manage the radio access in an efficient way that respects the different users conditions. However, optimizing the use of radio resources is a critical issue when spectrum has to be allocated with respect to end-users needs. Scheduling and queuing are key concepts of medium access mechanisms to ensure fairness among the users aiming at accessing the medium as well as to respond to high-priority users demands.

On the other hand, to achieve an efficient scheduling in a heterogeneous context where users have different level of QoS requirements, a service differentiation scheme is crucial for end-to-end QoS provisioning. In the WiMedia solution, we have seen that none of the proposed medium access mechanisms is based on an efficient service differentiation scheme that ensures prioritization without causing access problems. Therefore, we define in this section a service differentiation model for UWB users based on service classification and weight assignment.

4.2.1 Service differentiation

Since multimedia applications or real-time services are key applications for next generation wireless networks, especially in high-rate UWB networks, it is desirable to assign them a high level of priority in any radio access mechanism. A two-level service classification model is proposed in this chapter to ensure the prioritization principle and to respond to next generation systems QoS requirements. Consequently, we classify the UWB service types into two classes:

1. Hard-QoS class: This class is defined for applications or services that require strong QoS support, more precisely real-time or multimedia applications. Voice and video services for instance are non delay-tolerant applications; they have thus strict QoS requirements and they definitely belong to this class.
2. Soft-QoS class: This class is dedicated to applications that don't have strict QoS requirements, more precisely non real-time or data applications. BE and file transfer services for instance are delay-tolerant applications. Thus, they belong to this class.

Data rate (Mbps)	Constellation	Coding rate (r)	λ
53.3	QPSK	1/3	1.49
80	QPSK	1/2	1.57
110	QPSK	1/3	1.52
160	QPSK	1/2	1.57
200	QPSK	5/8	1.82
320	DCM	1/2	1.85
400	DCM	5/8	1.82
480	DCM	3/4	1.80

Table 3. WiMedia data rates and associated parameter λ.

4.2.2 Weight assignment

The defined service classification scheme offers a two-level priority-based model which affects the scheduling decision. Effectively, we assign a class weight to the different users or applications belonging to the two defined classes. A higher weight is thus to be assigned to the service type with strict QoS requirements.

Our weight assignment model is divided into two parts: fixed class weight assignment and dynamic service weight assignment.

Fixed class weight

According to our two-level service classification model, the priority level of the hard-QoS users is set to be two times greater than the priority level of the soft-QoS users. Weight $q = 2$ is thus attributed to the hard-QoS class and weight $q = 1$ to the soft-QoS class.

Dynamic service weight

Since different services belonging to the same class may have different QoS requirements, we define a dynamic service weight that ensures an additional level of differentiation between users according to their requested data rates. Consequently, a user k is assigned a service weight s_k defined as

$$s_k = 1 + \frac{R_k - R_{\min}}{R_{\max} - R_{\min}} \tag{7}$$

where R_k is the user k requested data rate, $R_{\min}$ and $R_{\max}$ are the lowest and the highest data rates respectively, taken dynamically from WiMedia rate modes as presented in Table 1. Thereby, this service weight gives advantage to users having higher data rate requirements. Note that this dynamic weight assignment which depends on the WiMedia specifications can be applied in any other system by adjusting the values of $R_{\min}$ and $R_{\max}$. This reflects the flexibility and the generality of this weight assignment approach.

Absolute user weight

Provided by the MAC layer, the fixed and dynamic weights definition ensures an adaptive rate differentiation for the end-users according to their requirements and to the system constraints. Accordingly, the absolute user weight W is the combination of the class weight with the service weight defined as

$$W_k = q_k \times s_k \tag{8}$$

where q_k is the user k class weight and s_k its service weight.

4.3 Analytical study for the multiuser optimization problem

In order to address the resource allocation matter in a multiuser context under QoS requirements, we follow an analytical study by deriving a constrained optimization problem. Since UWB communication systems are based on an underlay usage of the spectrum obtained under tough power spectral density limitations, there is no necessity to minimize the total power transmission. MA technique is however of interest for our aimed multiuser allocation scheme since we want to allocate sub-bands to different users having different data rate requirements. As our objective is to ensure fairness among the different users while satisfying high-priority users, we actually define our optimization goal as:

- Optimizing the resource allocation under the power constraint imposed by UWB systems. Note that the power spectral density constraint is transformed into a total power constraint. This is justified by the fact that, in our allocation scheme, we need to differentiate between the heterogeneous users by assigning them different power levels that respect the different QoS requirements.
- Maximizing the total data rate of the soft-QoS users while guaranteeing a certain level of transmission rate for the hard-QoS users.

4.3.1 Problem formulation

We consider a system that consists of K UWB users aiming at accessing the network. The users are classified into two groups; the first K_h users are hard-QoS users and the remaining

$K - K_h$ users are soft-QoS users. We first derive the expression of the rate used for the problem formulation. The rate of a user k in a sub-band b is expressed as

$$r_{k,b} = \log_2(1 + P_{k,b}\mathrm{E}_{k,b}) \tag{9}$$

where $P_{k,b}$ is the allocated power of user k in sub-band b and $\mathrm{E}_{k,b}$ the effective SINR of user k in sub-band b. Actually, the advantage of expressing the rate in terms of the effective SINR is twofold: First, in the sub-band allocation the effective SINR results from mapping the instantaneous subcarrier SINRs to one scalar value by sub-band. This reduces the computation cost of the rate since the effective SINR values are already computed by the new physical layer entity previously defined. Second, considered as a cross-layer metric, the effective SINR acts as a link between the physical data rate and the MAC user requested rate via the exploitation of λ parameter as shown in Table 3.
The optimization problem can thus be formulated as

$$\begin{aligned} \mathrm{P}: \quad & \max_{S_k, P_{k,b}} \sum_{k=K_h+1}^{K} \sum_{b \in S_k} r_{k,b} \\ & \textit{subject to} \sum_{b \in S_k} r_{k,b} \geq R_k, \quad k = 1, \ldots, K_h \\ & \sum_{k=1}^{K} \sum_{b=1}^{B} P_{k,b} \leq P_T \end{aligned} \tag{10}$$

where B is the total number of sub-bands, R_k the hard-QoS user k required data rate, S_k the set of sub-bands assigned to user k. In our case, $S_1, S_2, .., S_k$ are disjoint and each user is assigned one sub-band during one time interval. This problem is a mixed integer linear programming problem since S_k are integer variables. Consequently, the problem is classified as NP-hard. A method that makes the problem solvable is to relax the constraint that each sub-band is assigned to one user only. This approach is used in (Zhang & Letaief, 2004). The idea is to allow the users to time-share each sub-band by defining a new parameter $\omega_{k,b}$, which represents the time-sharing factor for user k in sub-band b. The optimization problem can then be stated as

$$\begin{aligned} \mathrm{P}: \quad & \max_{P_{k,b}, \omega_{k,b}} \sum_{k=K_h+1}^{K} \sum_{b=1}^{B} \omega_{k,b} \log_2\left(1 + \frac{P_{k,b}\mathrm{E}_{k,b}}{\omega_{k,b}}\right) \\ & \textit{subject to} \sum_{b=1}^{B} \omega_{k,b} \log_2\left(1 + \frac{P_{k,b}\mathrm{E}_{k,b}}{\omega_{k,b}}\right) \geq R_k, \quad k = 1, \ldots, K_h \\ & \sum_{k=1}^{K} \omega_{k,b} = 1, \quad \forall b \qquad 0 \leq \omega_{k,b} \leq 1 \quad \forall k, b \\ & \sum_{k=1}^{K} \sum_{b=1}^{B} P_{k,b} \leq P_T \end{aligned} \tag{11}$$

The latter optimization problem is a convex optimization problem since it has the following characteristics:

- The objective function of the maximization problem is concave since it is a linear combination of concave functions.

- The first and third constraints (inequality constraints) of the problem are convex.
- The second constraint (equality constraint) is affine.

Consequently, using the properties of a convex optimization problem, we derive the Lagrangian of the problem:

$$L = \sum_{k=K_h+1}^{K} \sum_{b=1}^{B} \omega_{k,b} \log_2(1+\frac{P_{k,b}\mathrm{E}_{k,b}}{\omega_{k,b}}) + \sum_{k=1}^{K_h} \alpha_k \left(\sum_{b=1}^{B} \omega_{k,b} \log_2(1+\frac{P_{k,b}\mathrm{E}_{k,b}}{\omega_{k,b}}) - R_k\right) + \sum_{b=1}^{B} \beta_b (1-\sum_{k=1}^{K} \omega_{k,b}) + \gamma(P_T - \sum_{k=1}^{K}\sum_{b=1}^{B} P_{k,b}) \tag{12}$$

where α_k, β_b and γ are the Lagrange multipliers for the different constraints of the optimization problem. Besides, to find the optimal solution of the problem, we need the Karush–Kuhn–Tucker or KKT conditions (Bertsekas, 1999). Let $\omega^*_{k,b}$ and $P^*_{k,b}$ denote the optimal solution. The KKT conditions of the formulated problem are given by

$$\begin{aligned}
&1)\ \frac{\partial L}{\partial P^*_{k,b}} \begin{cases} =0, & P^*_{k,b} > 0 \\ <0, & P^*_{k,b} = 0 \end{cases} \\
&2)\ \frac{\partial L}{\partial \omega^*_{k,b}} \begin{cases} <0, & \omega^*_{k,b} = 0 \\ =0, & \omega^*_{k,b} \in \left]0,1\right[\\ >0, & \omega^*_{k,b} = 1 \end{cases} \\
&3)\ \alpha_k \left(\sum_{b=1}^{B} \omega_{k,b} \log_2(1+\frac{P_{k,b}\mathrm{E}_{k,b}}{\omega_{k,b}}) - R_k\right) = 0
\end{aligned} \tag{13}$$

Applying the first KKT condition, we obtain:

$$\begin{aligned}
P^*_{k,b} &= \omega_{k,b}\left(\frac{\alpha_k}{\gamma \ln 2} - \frac{1}{\mathrm{E}_{k,b}}\right), && \text{for } k = 1,..,K_h \\
P^*_{k,b} &= \omega_{k,b}\left(\frac{1}{\gamma \ln 2} - \frac{1}{\mathrm{E}_{k,b}}\right), && \text{for } k = K_h+1,..,K
\end{aligned} \tag{14}$$

Then, the second KKT condition derives:

$$\begin{aligned}
&\alpha_k \left[\log_2(1+\frac{\mathrm{E}_{k,b}P_{k,b}}{\omega_{k,b}}) - \frac{1}{\ln 2}\left(\frac{\mathrm{E}_{k,b}P_{k,b}}{\omega_{k,b}+\mathrm{E}_{k,b}P_{k,b}}\right)\right] - \beta_b = 0, && \text{for } k = 1,..,K_h \\
&\log_2(1+\frac{\mathrm{E}_{k,b}P_{k,b}}{\omega_{k,b}}) - \frac{1}{\ln 2}\left(\frac{\mathrm{E}_{k,b}P_{k,b}}{\omega_{k,b}+\mathrm{E}_{k,b}P_{k,b}}\right) - \beta_b = 0, && \text{for } k = K_h+1,..,K
\end{aligned} \tag{15}$$

Substituting (14) into (15) we get:

$$\begin{aligned}
&\alpha_k \left[\log_2\left(\frac{\alpha_k \mathrm{E}_{k,b}}{\gamma \ln 2}\right) - \frac{1}{\ln 2}\left(1-\frac{\gamma \ln 2}{\alpha_k \mathrm{E}_{k,b}}\right)\right] - \beta_b = 0, && \text{for } k = 1,..,K_h \\
&\log_2\left(\frac{\mathrm{E}_{k,b}}{\gamma \ln 2}\right) - \frac{1}{\ln 2}\left(1-\frac{\gamma \ln 2}{\mathrm{E}_{k,b}}\right) - \beta_b = 0, && \text{for } k = K_h+1,..,K
\end{aligned} \tag{16}$$

After having used the time-sharing factor to find the optimal solution, we now go backward and enforce that one sub-band is assigned to one user only during one time interval. Therefore, we consider that $\omega_{k,b}$ cannot take values other than 0 or 1. Consequently,

$$\omega^{*}_{k,b} = \begin{cases} 1, & H_{k,b} > \beta_b \\ 0, & H_{k,b} < \beta_b \end{cases} \tag{17}$$

where $H_{k,b}$ is defined as:

$$\begin{aligned} H_{k,b} &= \alpha_k \left[\log_2\left(\frac{\alpha_k \mathrm{E}_{k,b}}{\gamma \ln 2}\right) - \frac{1}{\ln 2}\left(1 - \frac{\gamma \ln 2}{\alpha_k \mathrm{E}_{k,b}}\right) \right], && \text{for } k = 1,..,K_h \\ H_{k,b} &= \log_2\left(\frac{\mathrm{E}_{k,b}}{\gamma \ln 2}\right) - \frac{1}{\ln 2}\left(1 - \frac{\gamma \ln 2}{\mathrm{E}_{k,b}}\right), && \text{for } k = K_h + 1,..,K \end{aligned} \tag{18}$$

We conclude that, for a selected sub-band *b*, the user *k* having the highest *Hk,b* is assigned the sub-band. In other words, for a sub-band *b*, if *Hk,b* are different for all *k* then

$$\omega^{*}_{k',b} = 1 \text{ , } \omega^{*}_{k,b} = 0 \qquad \text{for all } k \neq k' \tag{19}$$

Where

$$k' = \arg\max_{k} H_{k,b} \tag{20}$$

Afterwards, we derive the last KKT condition that characterizes the hard-QoS users rate constraint:

$$r_{k,b} = \sum_{b=1}^{B} \omega_{k,b} \log_2\left(1 + \frac{P_{k,b}\mathrm{E}_{k,b}}{\omega_{k,b}}\right) \geq R_k \tag{21}$$

Substituting (14) into (21) we get:

$$r_{k,b} = \sum_{b=1}^{B} \omega_{k,b} \log_2\left(\frac{\alpha_k \mathrm{E}_{k,b}}{\gamma \ln 2}\right) \geq R_k \tag{22}$$

As a result, to obtain the optimal solution, we have to compute the optimal power allocation function $P_{k,b}$ and the optimal sub-band allocation function $H_{k,b}$. To do so, we need to find the set of a_k such that the hard-QoS users rate constraint given in (22) is satisfied.

4.3.2 Mathematical characteristics of the optimal solution

To solve the formulated optimization problem, we first study the characteristics of the sub-band and power allocation functions given in (14) and (18) respectively. These two functions have the following properties:

- First, they are monotonically increasing with respect to $\mathrm{E}_{k,b}$. This means that, for a selected sub-band, the user having better channel conditions has more chance to be assigned this sub-band with a good power level.
- Second, the two allocation functions are monotonically increasing with respect to a_k. This can be viewed as a result of the service differentiation principle. In other terms, the functions depend on the user priority and thus, the stricter the user requirements, the higher the value of αk and consequently the higher the value of these functions.

- Third, we conclude from the hard-QoS users constraint given in (22) that a_k is monotonically increasing with respect to R_k.

As a result, the power and the sub-band allocation functions depend on the rate constraints of the users, in particular the hard-QoS users which have strict data rate requirements.

4.3.3 Optimal power and sub-band allocation algorithm

Based on the above observations, we propose an iterative algorithm for the search of the optimal sub-band and power allocations. The process consists in incrementing a_k iteratively by a small value δ until reaching the hard-QoS users data rate request while respecting the power constraint.

The algorithm is detailed in Algorithm 1. We first start by initializing the a_k by a value slightly greater than one. Then, we process the sub-band allocation based on the defined a_k value by computing $H_{k,b}$ using (18) and finding $\omega_{k,b}$ and k' using (19) and (20). We test afterwards the rate constraint of the hard-QoS users by using (22). While there are hard-QoS users not satisfying their rate constraints, we increment their corresponding a_k values by δ.

1. Initialization

alpha = 1;

a_k = alpha + δ, for $k = 1,.., k_h$

2. Sub-band allocation

a. **for** sub-band $b = 1,..,B$

compute $H_{k,b}$ using (18) for all k

obtain $\omega_{k,b}$ and k' using (19) and (20)

b. **for** $k = 1,..,k_h$

compute r'_k using (22)

c. **for** $k = 1,..,k_h$

find $\tilde{k}$ with $r'_{\tilde{k}} < R_{\tilde{k}}$ and $r'_{\tilde{k}} - R_{\tilde{k}} \leq r'_k - R_k$

d. **while** $r'_{\tilde{k}} < R_{\tilde{k}}$

$\alpha_{\tilde{k}} = \alpha_{\tilde{k}} + \delta$

repeat a., b. and c.

3. Power allocation

a. compute $P_{k,b}$ using (14) for all k

b. compute $P'_T = \sum_{k=1}^{K} \sum_{b=1}^{B} P_{k,b}$

c. **if** $P'_T < P_T$

$\alpha_{\tilde{k}} = \alpha_{\tilde{k}} + \delta / 2$

else

$\alpha_{\tilde{k}} = \alpha_{\tilde{k}} - \delta / 2$

repeat 2. and 3. until $P'_T = P_T$

Algorithm 1. Iterative algorithm for optimal power and sub-band allocation.

Next, based on the obtained a_k values we process the power allocation by using (14). We then check the total power constraint. If we find that the total power exceeds the imposed total power, we decrement the a_k values by half the value of δ; otherwise we increment it by half of the same value.

4.3.4 Performance evaluation

In this section, we present some results of simulations obtained with the MB-OFDM UWB systems described previously. In these simulations, we consider an indoor environment, and we use the channel model adopted by the IEEE 802.15.3a task group, whose characteristics are listed in Table 2. In what follows, simulations are applied on channel model CM1 where a LOS case is considered and the transceiver spacing is less than 4 meters. Frames of 150 OFDM symbols are used, and each frame is transmitted on a different channel realization, from a total of 100 available realizations.
The objective is to study the performance of the allocation of three users in the same WiMedia frequency channel so that they can transmit simultaneously by assigning each user one sub-band according to the optimal allocation solution previously derived. Further, we compare our multiuser solution performance to the single-user WiMedia solution.
Thereby, we define a cross-layer performance metric called the satisfaction index (SI) defined as

$$SI(k) = \frac{\mathrm{E}_{k,b'}}{\max_{b} \mathrm{E}_{k,b}} \tag{23}$$

where $\mathrm{E}_{k,b'}$ is the effective SINR of the user k in its assigned sub-band b'. This metric evaluates the satisfaction level of a user k by using the effective SINR value which is correlated to its BER and its effective data rates via parameter λ as given in Table 2. It will be equal to one if the user is fully satisfied since it is assigned its best sub-band. The SI is consequently a QoS parameter and can be used to evaluate fairness among users.
In Fig. 3, we consider a 'three-users' allocation scheme. Four scenarios with different users rate requirements are studied where the three users are classified according to their highest allocation function value given by (18). We consider that all the users requesting a data rate greater than 200 Mbps are hard-QoS users. As evident from the obtained results, the proposed scheme respects the priority of the users so that the highest priority user is fully satisfied in all the cases since it is first assigned its most favorite sub-band. Consequently, the SI of the highest priority user is always equal to one. On the other hand, the SI of the other users depends on their rate requirements. We observe from the four scenarios that, for the second and third users, the SI is inversely proportional to the data rate requirement. For instance, if we compare the SI of the second user in the first and fourth scenarios, we see that it is more satisfied when its data requirement is lower. This is due to the fact that the satisfaction level is represented in terms of the effective SINR including parameter λ which is correlated to the data rate as shown in Table 2.
Fig. 4 shows the simulation results performed on the band group 1 {3168 - 4752} MHz of the WiMedia solution using a TFC (time-frequency code) sequence of [1 3 2] which provides a frequency hopping between the three bands at the end of each OFDM symbol. The BER is presented as a function of E_b/N_0, where E_b is the average energy per useful bit and N_0 is the AWGN power density. The ideal case of perfect channel estimation is considered. The

performance of the MB-OFDM system is presented for the different MB-OFDM data rates listed in Table 1. Evidently, the MB-OFDM system with a data rate of 53.3 Mbps has the lowest BER, since it uses the lowest coding rate with FDS and TDS techniques. Similarly, the system with the highest data rate of 480 Mbps has the worst performance in terms of BER due to its high coding rate of $r = 3/4$. Besides, if we compare data rates 53.3 and 110 Mbps, as well as data rates 80 and 160 Mbps, we notice that the difference in E_b / N_0 at a BER level of 10^{-4} is less than 0.5 dB. This means that applying the FDS reduces the data rate by half without offering a considerable E_b / N_0 gain. In addition, if we compare systems with data rates of 80 and 110 Mbps, we notice that the system with a data rate of 110 Mbps offers better performance even if it provides higher data rate. This is due to the fact that the FDS applied to the system with a data rate of 80 Mbps is not efficiently exploited.

To compare the performance of our proposed multiuser allocation scheme to that of the single-user WiMedia scheme, we present in Fig. 5 two different scenarios where we evaluate the performance of the hard-QoS users in terms of BER. In both scenarios, we consider two hard-QoS users transmitting at the same data rate of 400 Mbps in the first scenario and 320 Mbps in the second one. The soft-QoS user is transmitting at the same data rate of 53.3 Mbps in both scenarios. The average BER of the two hard-QoS users is computed and the result is compared to the single-user WiMedia transmitting at the same data rate. We can notice from the figure that in both scenarios the hard-QoS users in the multiuser allocation solution outperforms the single-user WiMedia by an average gain of 1.5 dB at a BER level of 10^{-4}. This is justified by the fact that in the proposed allocation solution, the hard-QoS users are given a high level of privilege that affects the quality of their assigned channels and consequently decreases their BER level.

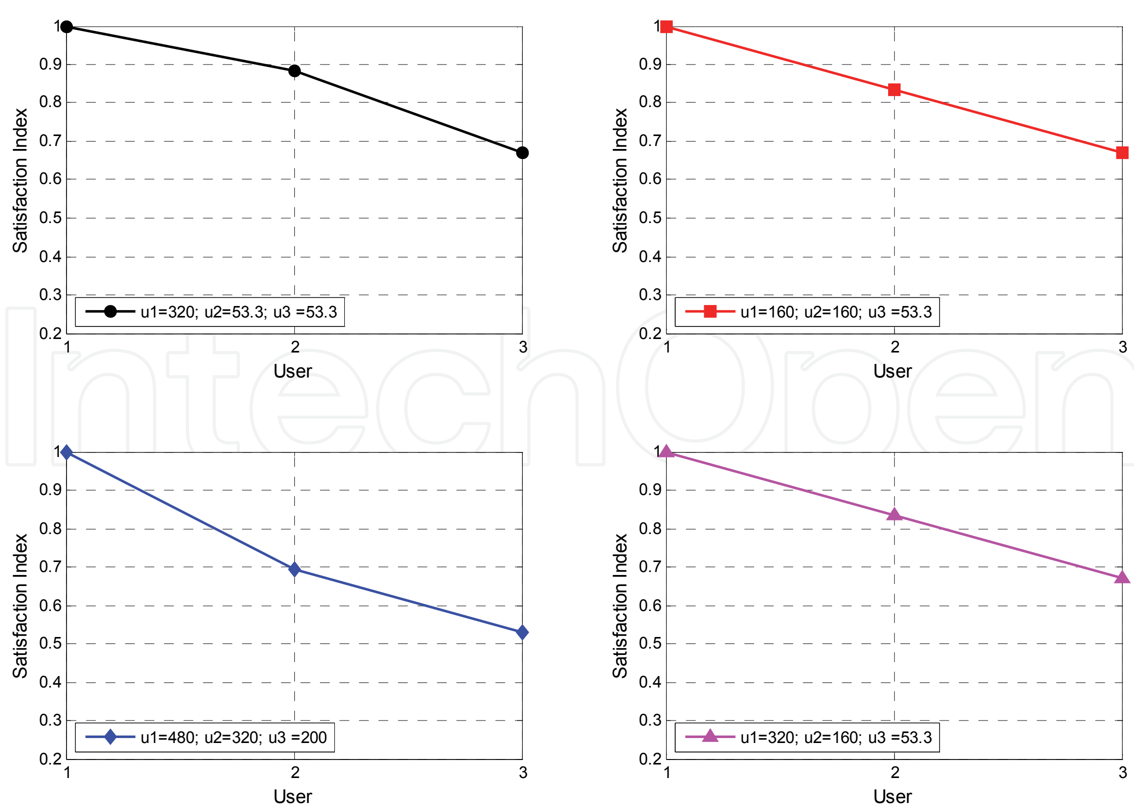

Fig. 3. Satisfaction Index of the 'three users' allocation scheme in different scenarios.

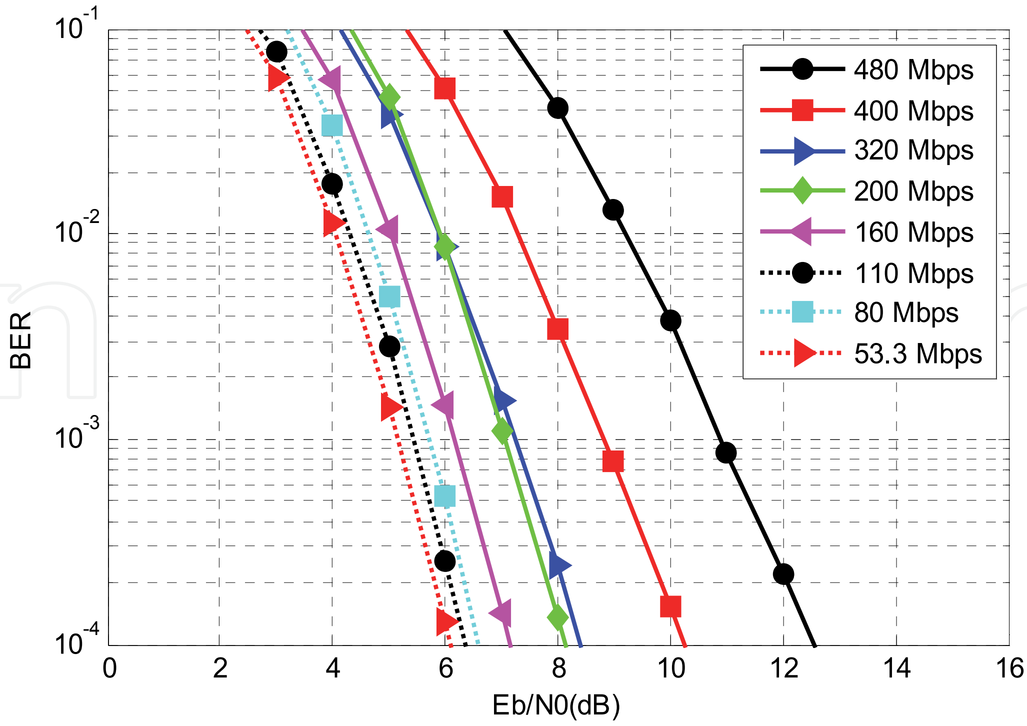

Fig. 4. Single-user WiMedia system performance on bands 1, 2 and 3, using channel model CM1 and considering a TFC frequency hopping between the three bands.

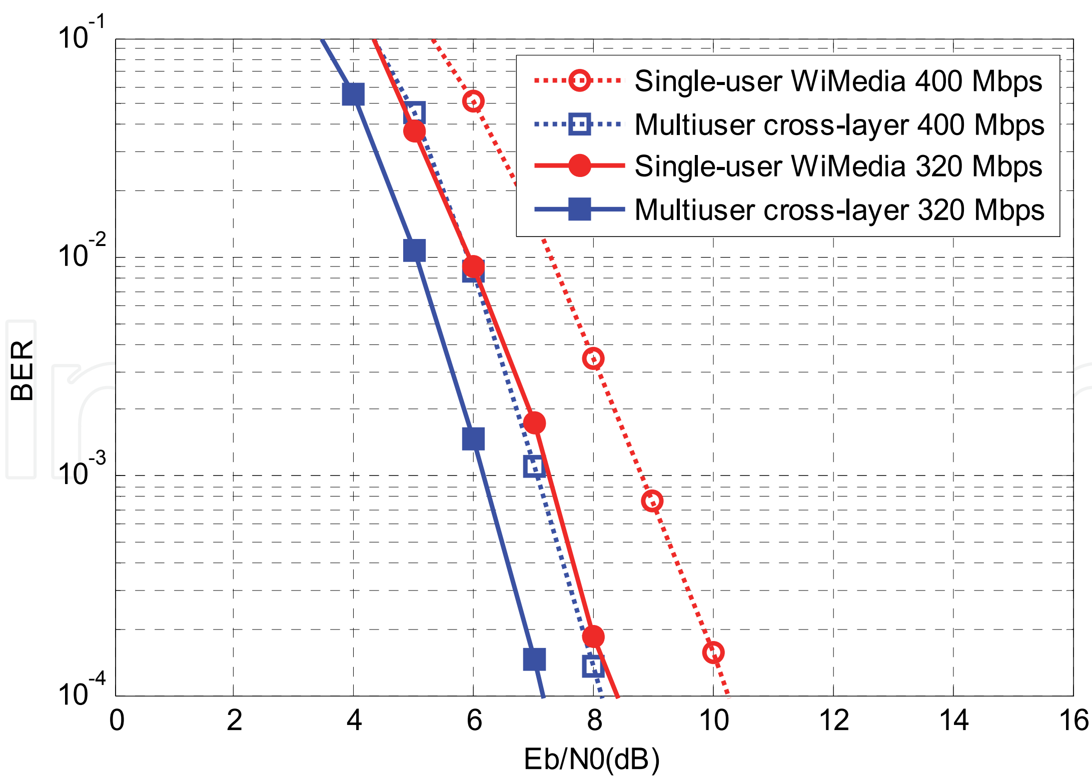

Fig. 5. Hard-QoS performance improvement in the proposed multiuser solution compared to the single-user WiMedia solution.

Fig. 6 shows further comparison between the proposed multiuser cross-layer scheme and the single-user WiMedia solution. To perform an efficient comparison, we consider scenarios where all the users are transmitting at the same data rate but belonging to different service classes. All the scenarios consist of two hard-QoS users and one soft-QoS user. The evaluation is performed for the eight WiMedia data rates, i.e. from 53.3 to 480 Mbps. The plotted curves represent the E_b/N_0 required to reach a BER level of 10^{-4} for each of the data rates. As shown in the figure, the highest priority user has a considerable gain compared to the lowest priority user. For instance, at a data rate equal to 480 Mbps, the highest priority user outperforms the lowest priority user with a 2.8 dB gain. On the other hand, the lowest priority user performance is slightly degraded compared to the WiMedia solution. This performance degradation of the low priority users can be viewed as a sacrifice for the sake of the high priority users to ensure their strict QoS requirements

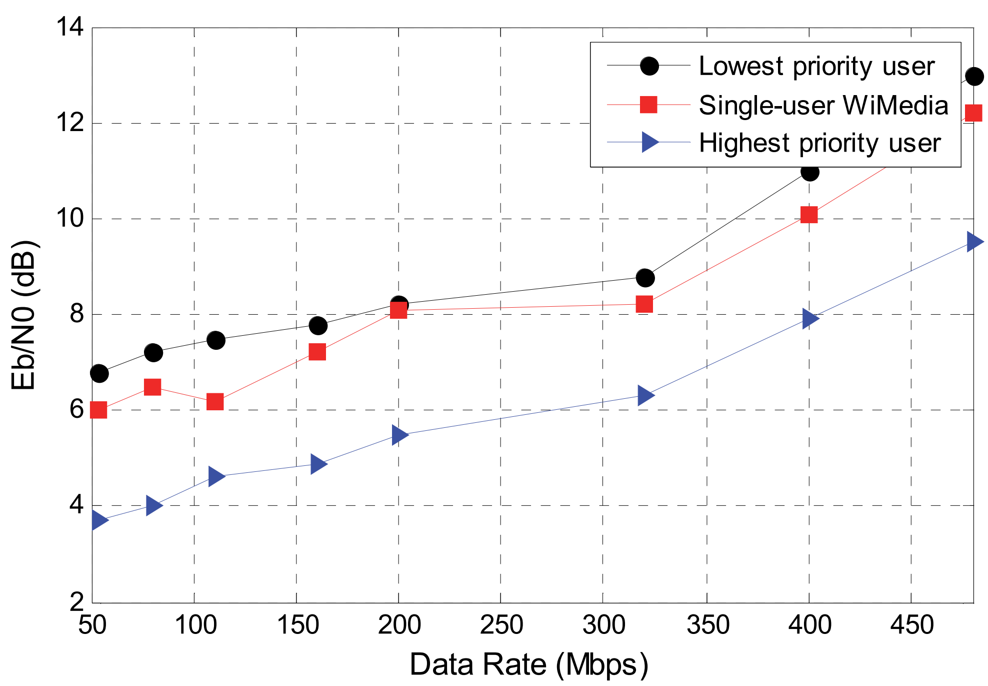

Fig. 6. Performance comparison of the highest and lowest priority users with the single-user WiMedia solution for the eight data rate modes.

5. Conclusion

In this chapter, we have investigated the sub-band and power allocation for MB-OFDM UWB systems in a multiuser context taking into account the users QoS requirements. For this purpose, we have defined new PHY-MAC metrics that are at the core of the cross-layer allocation scheme, so that new functionalities are added in the PHY and MAC layer respectively. While the PHY layer task is achieved through the use of the effective SINR method, the MAC layer is responsible for differentiating and classifying the users by assigning them different QoS weights.

We have then studied the multiuser allocation problem analytically by formulating a constrained multiuser optimization problem. An optimal solution for the sub-band and the power allocation has been thus carried out. To evaluate the performance of the different users, we have defined a satisfaction index parameter considered as a cross-layer metric to assess the QoS level of the different users. Simulation results have shown that the new multiuser allocation scheme can guarantee a good level of QoS for users having strict QoS requirements by adopting a strict priority-based approach in any 'three-users' allocation scenario. This priority-based approach gives advantage to the highest priority user that is totally satisfied while the other users satisfaction depends on their constraints and requirements. Compared to the single-user WiMedia solution, the proposed multiuser scheme is advantageous for hard-QoS users and slightly inconvenient for soft-QoS users. However, the performance degradation of the soft-QoS is tolerable since these users QoS requirements are less restrictive.

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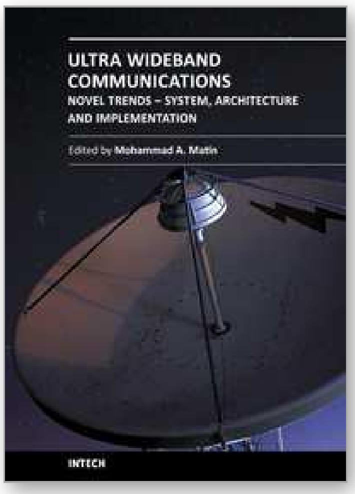

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