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Research Article

Time-Frequency Spectrum Sharing Scheme for Next Generation OFDM Systems

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Spectrum sharing and multiple-access techniques are challenging matters for future wireless communication systems. Orthogonal frequency division multiplexing (OFDM) has been considered as the most important physical layer candidate for the next generation wireless systems. Alternatively, multiband OFDM (MB-OFDM) approach has shown some novelty and efficiency for high-rate (HR) WPAN applications and so has been selected for future HR ultrawideband (UWB) systems. Based on an optimization problem formulation, we jointly consider resource allocation and scheduling to define a novel dynamic time-frequency spectrum sharing mechanism based on the MB-OFDM approach. Viewed as a cross-layer solution, the proposed MB-OFDM multiple-access (MB-OFDM-MA) scheme can achieve an efficient multiuser spectrum sharing under QoS constraints. While the optimization formulation results in a high-complexity time-frequency sharing solution, we propose a low-complexity suboptimal solution able to jointly provide fairness provision with the QoS support. Compared with traditional orthogonal frequency division multiple access (OFDMA), the simple time-frequency MB-OFDM-MA approach ensures a high level of fairness among the users while satisfying high-priority users having strict QoS requirements.

1. Introduction

Orthogonal frequency division multiplexing (OFDM) is a powerful scheme that is slated to be employed in the next generation wireless systems such as Long-Term Evolution (LTE), Worldwide Interoperability for Microwave Access (WiMAX), and high-speed WLAN standards such as 802.11n. It is expected to provide good performance at the physical layer and to enable efficient multiple-access mechanisms by employing orthogonal frequency multiple access (OFDMA) technique [1]. Thereby, in a multiuser context, the performance of OFDMA has to be linked to efficient and low-complexity spectrum sharing schemes that can respect the wireless channel conditions and satisfy the different users demands.

In the literature, the spectrum sharing issue is addressed either as a resource allocation problem using optimization strategies or as a time scheduling problem. Several studies investigate adaptive resource allocation for OFDMA systems using constrained optimization techniques [2–4]. Either considering margin adaptive or rate adaptive optimization techniques, all the resulting algorithms are nonlinear and have high computational complexity. Suboptimal algorithms are thus proposed in these studies to reduce the complexity. On the other hand, the studies that deal with scheduling in the time domain do not consider physical layer issues [5]. Few research works consider jointly the scheduling and the resource allocation matters. In [6], scheduling algorithms are developed for IEEE802.16d OFDMA-based broadband wireless access systems. In these algorithms, radio resource is dynamically shared by the users in both time and frequency domains. Fairness is ensured in this study but performance of the proposed algorithms is not examined for real-time applications. The authors in [7] define a joint resource allocation and scheduling scheme for IEEE 802.16 systems but without investigating optimization issues.

Alternatively to OFDM, multiband OFDM (MB-OFDM) is a new transmission technique proposed for high-rate (HR) ultrawideband (UWB) systems and supported by the WiMedia alliance [8, 9]. It consists in combining OFDM with

Table 1: WiMedia data rates and associated parameter λ.

Data rate (Mbps)	Modulation	Coding rate (r)	Frequency domain spreading	Time spreading factor (TSF)	Code bits per OFDM symbol	λ
53.3	QPSK	1/3	Yes	2	100	**1.49**
80	QPSK	1/2	Yes	2	100	**1.57**
110	QPSK	11/32	No	2	200	**1.52**
160	QPSK	1/2	No	2	200	**1.57**
200	QPSK	5/8	No	2	200	**1.82**
320	DCM	1/2	No	1	200	**1.85**
400	DCM	5/8	No	1	200	**1.82**
480	DCM	3/4	No	1	200	**1.80**

multibanding technique that divides the available bandwidth into subbands or blocks of subcarriers. Spectrum sharing and resource allocation are topics of interest in MB-OFDM-based systems. To this date, however, related research works are still limited.

Some 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 [10], 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 channel state information (CSI), the carriers and the power are dynamically allocated with the constraint of fixed data rate and fixed total power. In [11], 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 [12], 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.

A cross-layer subband and power allocation scheme is proposed in [13] for the multiband UWB systems. The subband 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. 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.

Based on optimization problem formulation and with respect to a study on the multiuser resource allocation for MB-OFDM UWB systems [14], the goal of this paper is to define a novel time-frequency MB-OFDM multiple-access (MB-OFDM-MA) scheme using a cross-layer approach and a joint consideration of resource allocation and scheduling. This scheme should be able to overcome the complexity limitation of the resource allocation in OFDMA systems while guaranteeing a high system performance and a good level of QoS and fairness provision. The paper is organized as follows. In Section 2, we present the MB-OFDM system model. An analytical study based on optimization problem formulation is given in Section 3. A joint resource allocation and scheduling optimization is derived leading to a time-frequency spectrum sharing optimization model. In order to reduce the complexity of the defined joint optimization, we present in Section 4 a novel low-complexity time-frequency spectrum sharing solution based on suboptimal subband allocation and scheduling solutions. The new proposed multiuser spectrum sharing scheme proves its ability to provide jointly fairness among users and QoS support for high-priority users. Finally, Section 5 presents simulation results showing the efficiency of the new multiuser scheme by evaluating the performance of the different users in terms of multiple QoS satisfaction metrics. Besides, some comparisons between the novel MB-OFDM-MA solution and the OFDMA scheme are drawn.

2. MB-OFDM System Model

In this section, we present the MB-OFDM solution as proposed by the WiMedia solution [8]. Thereby, the WiMedia MB-OFDM scheme consists in combining OFDM with a multibanding technique that divides the available band into 14 subbands of 528 MHz each. An OFDM modulation with 128 subcarriers is applied on each subband separately. Different data rates from 53.3 to 480 Mbps are obtained with the combined use of forward error correction (FEC), frequency-domain spreading (FDS), and time-domain spreading (TDS), as presented in Table 1. The constellation applied to the different subcarriers is either a quadrature phase-shift keying (QPSK) for low data rates or a dual carrier modulation (DCM) for high data rates. Note that in Table 1, a new parameter λ is introduced. This parameter will be defined in the next section and used for the exploitation of the CSI. Moreover, it is possible in the

WiMedia solution to exploit the two or three subbands of one band group through the use of a so-called time frequency code (TFC). TFC defines frequency hopping patterns applied to consecutive OFDM symbols. Without considering the resource allocation matter, TFC allows each user to benefit from frequency diversity over a bandwidth equivalent to the two or three subbands of one channel. However, the TFC strategy lacks in the ability to allocate bands optimally since the available bands are not assigned to each user according to its channel condition. We have thus to look for an alternative of the TFC in order to allocate the resources in an adaptive way that responds to the heterogeneous QoS requirements.

3. Analytical Study

3.1. Channel Information. In order to be aware of the physical conditions in the perspective of the resource allocation scheme, there is a need to exploit some channel parameters reflecting the channel quality of each user aiming at accessing the network. Assuming that the instantaneous signal to interference and noise ratio (SINR) for each subcarrier is known by each user through the CSI acquisition, it is possible to estimate the system level performance in terms of BER by using the effective SINR approach [15]. Note that the CSI is simply obtained through channel estimation process at each user station. Proposed in the 3GPP standardization, the effective SINR approach has been used as an effective link to system mapping method. The basic idea is to find a compression function that maps each sequence of varying SINRs to a single value that is correlated with the BER. This can be stated as

$$\mathrm{SINR}_{\mathrm{eff}} = -\lambda\left[\frac{1}{N}\sum_{i=1}^{N}\exp\left(-\frac{\mathrm{SINR}_i}{\lambda}\right)\right], \tag{1}$$

where N is the number of subcarriers in a subband, SINR_i is the ratio of signal to interference and noise for the ith subcarrier, and λ is a scaling factor that depends 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 as presented in Table 1.

In practice, based on the CSI knowledge, each user is capable to compute the effective SINR value in each subband by using (1). For instance, in the case of one channel divided into $B = 3$ subbands, and with $K = 3$ users, the physical layer information is reduced to the knowledge of only $B \times K = 9$ effective SINR scalar values.

3.2. Optimization Problem Formulation. In order to meet the QoS requirements of multimedia and real-time services, we formulate an optimization problem based on a service differentiation principle. A two-class-based model is defined as follows: class 1 is referred to as hard-QoS class for real-time or multimedia applications that require strict QoS requirements (i.e., multimedia applications), and class 2 is referred to as soft-QoS class for nonreal-time or data applications having less QoS constraints (i.e., data applications).

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 subband b is expressed as

$$r_{k,b} = \log_2\left(1 + P_{k,b}\mathrm{E}_{k,b}\right), \tag{2}$$

where $P_{k,b}$ is the allocated power of user k in subband b and $\mathrm{E}_{k,b}$ the effective SINR of user k in subband b. The optimization problem can thus be formulated as

$$\begin{aligned} &\max_{S_k, P_{k,b}} \quad \sum_{k=K_h+1}^{K}\sum_{b\in S_k} r_{k,b} \\ &\text{subject to} \quad \sum_{b\in S_k} r_{k,b} \geq R_k, \quad k = 1,\ldots,K_h \\ &\qquad\qquad \sum_{k=1}^{K}\sum_{b=1}^{B} P_{k,b} \leq P_T, \end{aligned} \tag{3}$$

where B is the total number of subbands, R_k is the hard-QoS user k required data rate, and S_k is the set of subbands assigned to user k. In our case, $S_1, S_2, \ldots, S_k$ are disjoint and each user is assigned one subband 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 subband is assigned to one user only. The idea is to allow the users to time-share each subband by defining a new parameter $\omega_{k,b}$, which represents the time-sharing factor for user k in subband b. The optimization problem can then be stated as

$$\begin{aligned} &\max_{P_{k,b},\omega_{k,b}} \quad \sum_{k=K_h+1}^{K}\sum_{b=1}^{B}\omega_{k,b}\log_2\left(1 + \frac{P_{k,b}\mathrm{E}_{k,b}}{\omega_{k,b}}\right) \\ &\text{subject to} \quad \sum_{b=1}^{B}\omega_{k,b}\log_2\left(1 + \frac{P_{k,b}\mathrm{E}_{k,b}}{\omega_{k,b}}\right) \geq R_k, \quad k = 1,\ldots K_h, \\ &\qquad\qquad \sum_{k=1}^{K}\omega_{k,b} = 1, \quad \forall b \quad 0 \leq \omega_{k,b} \leq 1 \quad \forall k,b, \\ &\qquad\qquad \sum_{k=1}^{K}\sum_{b=1}^{B} P_{k,b} \leq P_T. \end{aligned} \tag{4}$$

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

$$\begin{aligned} L = &\sum_{k=K_h+1}^{K}\sum_{b=1}^{B}\omega_{k,b}\log_2\left(1 + \frac{P_{k,b}\mathrm{E}_{k,b}}{\omega_{k,b}}\right) \\ &+ \sum_{k=1}^{K_h}\alpha_k\left(\sum_{b=1}^{B}\omega_{k,b}\log_2\left(1 + \frac{P_{k,b}\mathrm{E}_{k,b}}{\omega_{k,b}}\right) - R_k\right) \\ &+ \sum_{b=1}^{B}\beta_b\left(1 - \sum_{k=1}^{K}\omega_{k,b}\right) + \gamma\left(P_T - \sum_{k=1}^{K}\sum_{b=1}^{B}P_{k,b}\right), \end{aligned} \tag{5}$$

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. Let $\omega^*_{k,b}$ and $P^*_{k,b}$ denote the optimal solution, the KKT conditions of the formulated problem are given by

$$\begin{aligned}
&(1)\ \frac{\partial \mathrm{L}}{P^*_{k,b}} \begin{cases} = 0, & P^*_{k,b} > 0, \\ < 0, & P^*_{k,b} = 0 \end{cases} \\
&(2)\ \frac{\partial \mathrm{L}}{\omega^*_{k,b}} \begin{cases} < 0, & \omega^*_{k,b} = 0 \\ = 0, & \omega^*_{k,b} \in \,]0,1[, \\ > 0, & \omega^*_{k,b} = 1 \end{cases} \\
&(3)\ \alpha_k \left(\sum_{b=1}^{B} \omega_{k,b} \log_2 \left(1 + \frac{P_{k,b}\mathrm{E}_{k,b}}{\omega_{k,b}} \right) - R_k \right) = 0.
\end{aligned} \tag{6}$$

Applying the first KKT condition, we obtain

$$\begin{aligned}
P^*_{k,b} &= \omega_{k,b} \left(\frac{\alpha_k}{\gamma \ln 2} - \frac{1}{\mathrm{E}_{k,b}} \right), \quad \text{for } k = 1, \ldots, K_h, \\
P^*_{k,b} &= \omega_{k,b} \left(\frac{1}{\gamma \ln 2} - \frac{1}{\mathrm{E}_{k,b}} \right), \quad \text{for } k = K_h + 1, \ldots, K.
\end{aligned} \tag{7}$$

Then, the second KKT condition derives

$$\begin{aligned}
&\alpha_k \left[\log_2 \left(1 + \frac{\mathrm{E}_{k,b}P_{k,b}}{\omega_{k,b}} \right) - \frac{1}{\ln 2} \left(\frac{\mathrm{E}_{k,b}P_{k,b}}{\omega_{k,b} + \mathrm{E}_{k,b}P_{k,b}} \right) \right] - \beta_b = 0, \\
&\qquad \text{for } k = 1, \ldots, K_h, \\
&\log_2 \left(1 + \frac{\mathrm{E}_{k,b}P_{k,b}}{\omega_{k,b}} \right) - \frac{1}{\ln 2} \left(\frac{\mathrm{E}_{k,b}P_{k,b}}{\omega_{k,b} + \mathrm{E}_{k,b}P_{k,b}} \right) - \beta_b = 0, \\
&\qquad \text{for } k = K_h + 1, \ldots, K.
\end{aligned} \tag{8}$$

Substituting (7) into (8), we get

$$\begin{aligned}
&\alpha_k \left[\log_2 \left(\frac{\alpha_k \mathrm{E}_{k,b}}{\gamma \ln 2} \right) - \frac{1}{\ln 2} \left(1 - \frac{\gamma \ln 2}{\alpha_k \mathrm{E}_{k,b}} \right) \right] - \beta_b = 0, \\
&\qquad \text{for } k = 1, \ldots, K_h, \\
&\log_2 \left(\frac{\mathrm{E}_{k,b}}{\gamma \ln 2} \right) - \frac{1}{\ln 2} \left(1 - \frac{\gamma \ln 2}{\mathrm{E}_{k,b}} \right) - \beta_b = 0, \\
&\qquad \text{for } k = K_h + 1, \ldots, K.
\end{aligned} \tag{9}$$

After having used the time-sharing factor to find the optimal solution, we now go backward and enforce that one subband 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,

$$\omega^*_{k,b} = \begin{cases} 1, & H_{k,b} > \beta_b \\ 0, & H_{k,b} < \beta_b, \end{cases} \tag{10}$$

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

$$\begin{aligned}
H_{k,b} &= \alpha_k \left[\log_2 \left(\frac{\alpha_k \mathrm{E}_{k,b}}{\gamma \ln 2} \right) - \frac{1}{\ln 2} \left(1 - \frac{\gamma \ln 2}{\mathrm{E}_{k,b}} \right) \right], \\
&\qquad \text{for } k = 1, \ldots, K_h, \\
H_{k,b} &\log_2 \left(\frac{\mathrm{E}_{k,b}}{\gamma \ln 2} \right) - \frac{1}{\ln 2} \left(1 - \frac{\gamma \ln 2}{\mathrm{E}_{k,b}} \right), \\
&\qquad \text{for } k = K_h + 1, \ldots, K.
\end{aligned} \tag{11}$$

We conclude that, for a selected subband b, the user k having the highest $H_{k,b}$ is assigned the subband. In other words, for a subband b, if $H_{k,b}$ are different for all k, then

$$\omega^*_{k',b} = 1, \qquad \omega^*_{k,b} = 0 \quad \forall k \neq k', \tag{12}$$

where

$$k' = \arg \max_k H_{k,b}. \tag{13}$$

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

$$R'_{k,b} = \sum_{b=1}^{B} \omega_{k,b} \log_2 \left(1 + \frac{P_{k,b}\mathrm{E}_{k,b}}{\omega_{k,b}} \right) \geq R_k. \tag{14}$$

Substituting (7) into (14), we get

$$R'_{k,b} = \sum_{b=1}^{B} \omega_{k,b} \log_2 \left(\frac{\alpha_k \mathrm{E}_{k,b}}{\gamma \ln 2} \right) \geq R_k. \tag{15}$$

As a result, to obtain the optimal solution, we have to compute the optimal power allocation function $P_{k,b}$ and the optimal subband allocation function $H_{k,b}$. To do so, we need to find the set of α_k such that the hard-QoS users rate constraint given in (15) is satisfied.

3.3. Optimal Spectrum Allocation Algorithm. To solve the formulated optimization problem, we first study the characteristics of the subband and power allocation functions given in (7) and (11), respectively. These two functions have the following properties. (i) First, they are monotonically increasing with respect to $\mathrm{E}_{k,b}$. This means that, for a selected subband, the user having better channel conditions has more chance to be assigned this subband with a good power level. (ii) Second, the two allocation functions are monotonically increasing with respect to α_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 α_k and consequently the higher the value of these functions. (iii) Third, we conclude from the hard-QoS users constraint given in (15) that α_k is monotonically increasing with respect to R_k. As a result, the power and the subband allocation functions depend on the rate constraints of the users, in particular the hard-QoS users which have strict data rate requirements.

Based on the above observations, we propose an iterative algorithm for the search of the optimal subband allocation.

(1) **Initialization**
  alpha = 1;
  α_k = alpha + δ, for $k = 1,\ldots,k_h$
(2) **Subband allocation**
  (a) **for** subband $b = 1,\ldots,B$
    compute $H_{k,b}$ using (11) for all k
    obtain $\omega_{k,b}$ and k' using (12) and (13)
  (b) **for** $k = 1,\ldots,k_h$
    compute R'_k using (15)
  (c) **for** $k = 1,\ldots,k_h$
    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 (7) 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 subband allocation.

The process consists in incrementing α_k iteratively by a small value δ until reaching the hard-QoS users data rate request while respecting the power constraint.

As shown in Algorithm 1. We first start by initializing α_k by a value slightly greater than one. Then, we process the subband allocation based on the defined α_k value by computing $H_{k,b}$ using (11) and finding $\omega_{k,b}$ and k' using (12) and (13). We test afterwards the rate constraint of the hard-QoS users by using (15). While there are hard-QoS users not satisfying their rate constraints, we increment their corresponding α_k values by δ.

Next, based on the obtained α_k values we process the power allocation by using (7). We then check the total power constraint. If we find that the total power exceeds the imposed total power, we decrement the α_k values by half the value of δ; otherwise, we increment it by half of the same value.

Interestingly, due to the banding approach, MB-OFDM-MA reduces the complexity of the subcarrier assignment required in OFDMA which is considered as a combinatorial optimization problem with high computational complexity. On the other hand, an additional complexity arises in the derived optimal subband allocation. This complexity resides in the iterative process required by the optimal subband allocation function to find the set of α_k.

3.4. Time-Frequency Spectrum Sharing Optimization. From a 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 users are of great importance. Thereby, in order to increase the freedom level of the frequency resource allocation, we propose a joint resource allocation and scheduling model leading to a multiuser time-frequency spectrum sharing scheme. Based on the optimal allocation function derived in (11), we define hereafter a multiuser time-frequency optimization scheme that should allow different users to coexist in one subband while respecting the QoS requirements.

In the WiMedia solution, the channel time is divided into superframes; a superframe is the basic timing structure for frame exchange and is composed of two major parts: the beacon period (BP) and the data transfer period (DTP). The duration of the superframe is specified as 65536 μs, and the superframe consists of 256 medium access slots (MASs), which are all of equal length, 256 μs.

Thereby, three users can coexist in the same channel that consists of three subbands in the case of one MB-OFDM channel. The idea is thus to share the MASs of a superframe among multiple users whereas three users can transmit simultaneously in each MAS.

While B and K are the number of subbands and the total number of users, respectively, the idea is to classify the K users into two groups: a high-priority (HP) group of B users and a low-priority (LP) group of $K - B$ users. To do so, we arrange the K users in a decreasing order according to their $H_{k,b}$ values given by (11).

A first subband allocation is achieved; the HP users are assigned subbands according to their priority order; the highest priority user is assigned its most powerful subband, that is the subband having the greatest $E_{k,b}$ value.

After the first allocation, the remaining $K-B$ LP users are reclassified according to a new allocation function defined as the average of their $H_{k,b}$ values over the B subbands

$$\overline{H}_{k,b} = \frac{\sum_{b=1}^{B} H_{k,b}}{B}, \quad k = B+1,\ldots,K. \tag{16}$$

This modified metric is justified by the fact that these $K - B$ users do not have any assigned subband yet and that all the available subbands are already assigned to the HP users. Actually, we have to allow the LP group to share the assigned subbands with the HP group in an efficient time sharing way that respects all the QoS constraints. As this time sharing principle should respect the QoS support, the new allocation problem consists in finding, for each user in the LP group, the corresponding subband that maximizes its rate while minimizing the loss of rate of the HP user already occupying the subband. The problem can be formulated as

$$\begin{aligned} &\max_b r_{k',b}, \quad k' = B+1,\ldots,K \\ &\text{subject to } r_{k,b} \geq R_{k\,\min}, \quad k = 1,\ldots,B, \end{aligned} \tag{17}$$

where $R_{k\,\min}$ is the minimum tolerable data rate value of the HP user k. To solve this optimization problem, we introduce a subband sharing factor τ_b defined as

$$\tau_b = \frac{H_{k,b}}{\overline{H}_{k',b}}, \tag{18}$$

where $H_{k,b}$ and $\overline{H}_{k',b}$ are the allocation functions for the HP user k and the LP user k', respectively. This sharing factor

actually represents the spectrum usage advantage of the HP users on the LP users. Consequently, the sharing coefficients of HP user k and LP user k' in subband b are, respectively, defined as

$$\tau_{k,b} = \frac{\tau_b}{1+\tau_b}, \qquad \tau_{k',b} = \frac{1}{1+\tau_b}, \tag{19}$$

and it is important to note that $\tau_{k,b}+\tau_{k',b} = 1$, which indicates that the subband is occupied at 100% of the time. As a result, the new data rates of users k and k' sharing the same subband b are now defined by

$$r^*_{k,b} = \tau_{k,b} r_{k,b}, \qquad r'^*_{k',b} = \tau_{k',b} r'_{k',b}. \tag{20}$$

The solution of the sharing optimization problem given in (20) is then obtained by using a priority-based approach. Indeed, the time sharing is processed according to the classification of the LP users. Thus, the highest priority user in this LP group first starts a heuristic search for the corresponding subband that responds to (17) by using (20). The process is iterated for all the remaining LP users.

To better illustrate the proposed optimization spectrum sharing scheme, we present hereafter a case of six users aiming at sharing the three subbands of the WiMedia solution. We consider the following user classification:

$$\underbrace{U_1 > U_2 > U_3}_{\text{high-priority}} > \underbrace{U_4 > U_5 > U_6}_{\text{low-priority}}, \tag{21}$$

which results from the allocation functions computation given by $H_{k,b}$ and $\overline{H}_{k',b}$. Initially, suppose that the HP users are first assigned the subbands according to their $H_{k,b}$ values. Then, suppose that, after the computation of (18) and (20) and solving (17), we obtain the following matrix containing the $\tau_{k,b}$ values for all the users in the subbands they aim at sharing:

$$\begin{pmatrix} \tau_{U_1,1} & 0 & 0 \\ 0 & 0 & \tau_{U_2,3} \\ 0 & \tau_{U_3,2} & 0 \\ 0 & \tau_{U_4,2} & 0 \\ 0 & 0 & \tau_{U_5,3} \\ \tau_{U_6,1} & 0 & 0 \end{pmatrix}. \tag{22}$$

The latter matrix gives a possible optimized sharing scheme for the six users, where U_4 shares subband 2 with U_3, U_5 shares subband 3 with U_2, and U_6 shares subband 1 with U_1.

4. Proposed Low-Complexity Time-Frequency Spectrum Sharing Solution with Fairness Provision

Optimizing the use of the spectrum by adjusting the main transmission parameters is the main purpose. However, the spectrum sharing solution presented in the previous section has a high computation cost. The complexity of the defined spectrum sharing scheme lies on two main aspects. First, the iterative process defined for the subband allocation and the computation of the optimal allocation function $H_{k,b}$ require a high computation complexity. Second, the heuristic search proposed to schedule the users also involves an additional computation cost into the heuristic search proposed to schedule the users also involves an additional computation cost. We present in this section a low-complexity and practical cross-layer spectrum sharing scheme.

Since the complexity of the optimal spectrum sharing solution resides in the complexity of both resource allocation optimization and scheduling optimization, we will reduce the whole complexity by defining suboptimal subband allocation and suboptimal time scheduling solutions.

4.1. Suboptimal Subband Allocation Function. By analyzing the optimal allocation function given by (11), it comes that this function is monotonically increasing with respect to $\mathrm{E}_{k,b}$ and α_k. In addition, α_k is monotonically increasing with respect to R_k as given by (15). Thus, the allocation function depends on the user rate requirement. In order to reduce the complexity due to the computation of α_k, we define a new parameter having the same mathematical characteristics as α_k, but requiring a lower complexity computation. This new parameter is the user data rate weight r_k defined as

$$r_k = 1 + \frac{R_k - R_{\min}}{R_{\max} - R_{\min}}, \tag{23}$$

where R_k, $R_{\min}$, and $R_{\max}$ are, respectively, the requested data rate of user k, the lowest and highest data rates taken from WiMedia rate modes (Table 1). Provided by the MAC layer, this weight definition scheme ensures an adaptive rate classification of the different users according to their requirements and to the system model. Consequently, we define a low-complexity cross-layer allocation function $H'_{k,b}$, having the same mathematical behaviors as the optimal function $H_{k,b}$, and based on the product of the user rate weight by the user effective SINR in a subband. It is given by

$$H'_{k,b} = r_k \mathrm{E}_{k,b}. \tag{24}$$

4.2. Suboptimal Time-Scheduling Solution. To reduce the complexity of the optimal sharing solution, we propose a novel time scheduling mechanism called the nearest priority sharing (NPS) based on a priority principle that shares the time among the users in a simple way according to their priority order. As described before, the different users are arranged according to their allocation function and then classified into two groups: HP and LP. While the HP users are first assigned the B subbands, the LP users aim at sharing these assigned subbands with them during one superframe. The idea of the NPS mechanism is depicted in Figure 1; the users of the LP group share, in a priority order, the same subband assigned to their nearest-priority user of the HP group, provided that this latter user has the minimum number of users already sharing the same spectrum with.

This suboptimal scheduling solution has the same characteristics as the optimal solution resulting from the

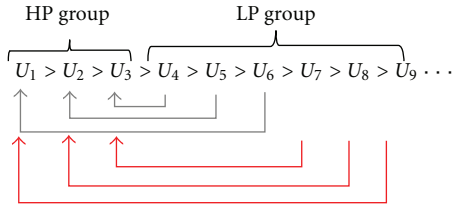

Figure 1: The principle of the NPS mechanism.

optimization problem given by (17). Indeed, the optimal sharing is done in a priority-based principle. Similarly, the NPS mechanism respects the same priority-based approach, yet forces the LP users to share the subbands with the HP users by using the inverted priority order, that is the highest priority user of the LP group coexists with the lowest priority user of the HP group, and the lowest priority user of the LP group coexists with the highest priority user of the HP group.

4.3. Low-Complexity Time-Frequency Spectrum Sharing with Fairness Provision. As stated before, a priority-based approach is used to arrange the users in a decreasing order according to a weight value. The weight $\mathcal{Q}$ of each user k is defined as its highest cross-layer suboptimal allocation function value over the subbands. It is given by

$$\mathcal{Q}_k = \max_b H'_{k,b}. \tag{25}$$

Then, since the suboptimal time-scheduling principle provides a high level of simplicity and flexibility, we define a fair time-frequency scheduling mechanism called Weighted Cyclic Rounding (WCR) based on the NPS principle. The idea behind this mechanism is to share the time proportionally to the users weights $\mathcal{Q}_k$ while permuting cyclically, after each user round, the priority order of the users for the subband assignments. Thereby, while each frame time (superframe) is shared dynamically among the users, a user round O_k, which consists of a certain number of MASs, is defined as follows:

$$\frac{\mathcal{Q}_1}{O_1} = \frac{\mathcal{Q}_2}{O_2} = \cdots = \frac{1}{T_F}, \tag{26}$$

where $\mathcal{Q}_1, \mathcal{Q}_2, \ldots, \mathcal{Q}_k$ are the normalized users weights and T_F is the total superframe duration. The WCR is achieved using a priority-based circular shift approach as illustrated in Figure 2(a). For example, the highest priority user U_1 is assigned first its best subband for a round cycle equal to O_4; then a first permutation is applied so that the second priority user U_2 is placed at the top of the priority order and assigned its best subband for a round cycle equal to O_2 and so on.

4.3.1. Multiuser Round Sharing. In order to share one round cycle among multiple users in a multiuser scenario, we define a round sharing scheme. The idea is to time-share the MASs of one round cycle among multiple users whereas, in frequency, B users can transmit simultaneously during one MAS duration.

Similarly to the optimal scheme, the HP users are assigned subbands according to their priority order; the highest priority user is assigned its most powerful subband, that is the subband that has the greatest $E_{k,b}$ value. Secondly, the users of the LP group have to share the already assigned subbands with the HP group users during one round cycle.

In The Frequency Domain. The sharing is done according to the NPS principle. For instance, the highest priority user of the LP group shares the same subband with the lowest priority user of the HP group and so on.

In The Time Domain. A time-sharing factor of user k in subband b is defined as follows:

$$\tau_{k,b} = \frac{\mathcal{Q}_{s_b^k}}{\text{sum}_{s_b^k}\left(\mathcal{Q}_{s_b^k}\right)}, \tag{27}$$

where s_b^k is the disjoint set of users sharing the subband b obtained by applying the NPS mechanism. This sharing factor represents the spectrum usage advantage of the HP users on the LP users. As a result, multiple users can share, using a priority-based principle, one subband during one round cycle of a superframe as illustrated in Figure 2(b).

Depicted in Figure 3, the low-complexity time-frequency spectrum sharing can be considered as an answer to the multiuser access problem in the WiMedia solution where the use of TFC is limiting the number of users aiming at sharing one superframe in one WiMedia channel to three users only.

5. Performance Evaluation

5.1. Channel Model. The channel used in this study is the one adopted by the IEEE 802.15.3a committee for the evaluation of UWB proposals [16]. This model is a modified version of Saleh-Valenzuela model for indoor channels [17], 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

$$h_i(t) = G_i \sum_{z=0}^{Z_i} \sum_{p=0}^{P_i} \alpha_i(z,p)\,\delta\left(t - T_i(z) - \tau_i(z,p)\right), \tag{28}$$

where G_i is the log-normal shadowing of the ith channel realization, $T_i(z)$ the delay of cluster z, and $\alpha_i(z,p)$ 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.

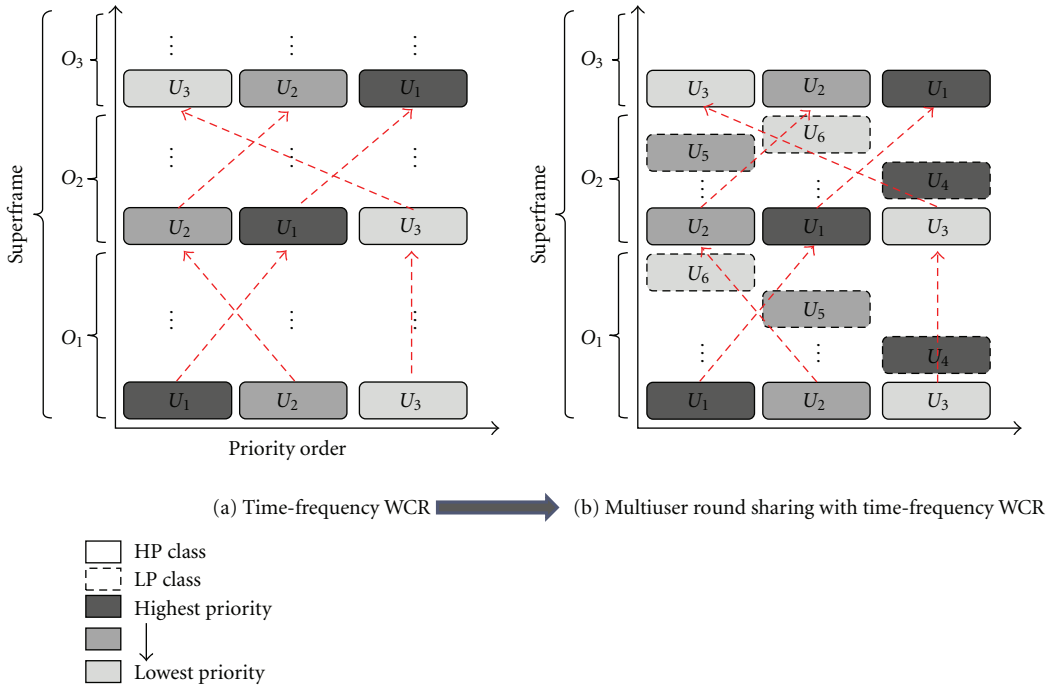

FIGURE 2: Weighted cyclic rounding mechanism and the associated round sharing principle.

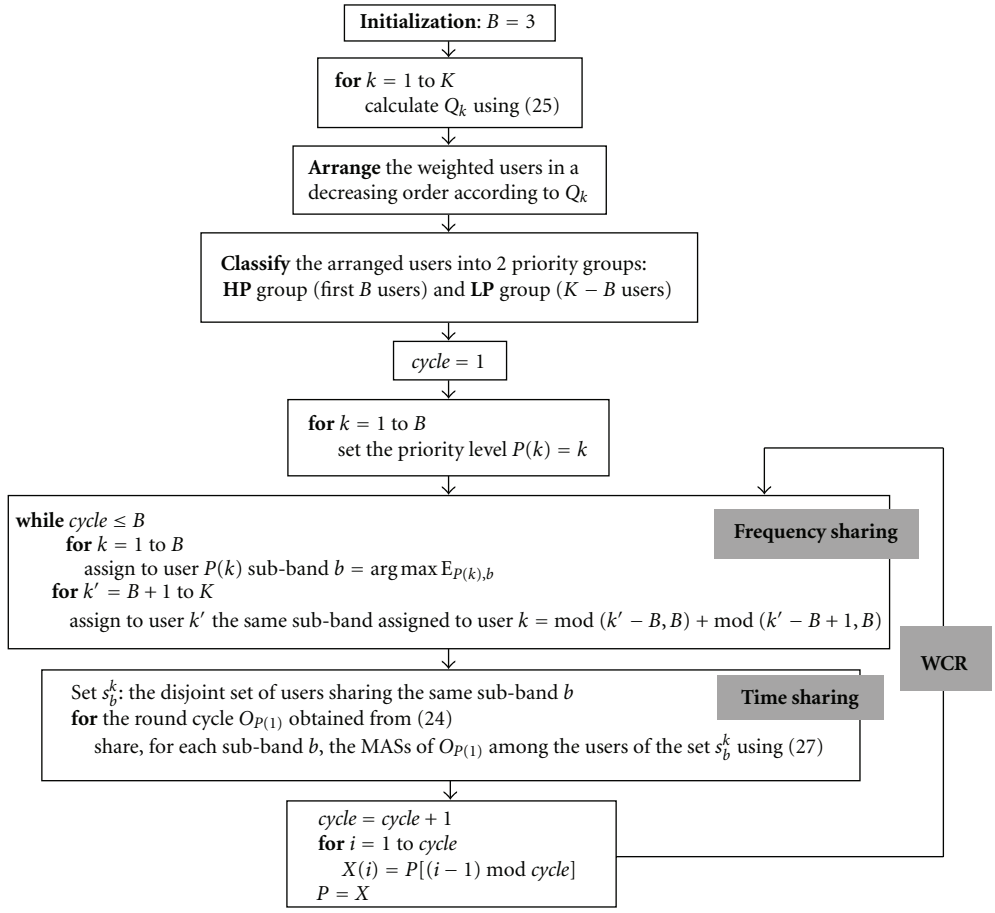

FIGURE 3: Proposed time-frequency spectrum sharing algorithm.

For the simulation scenarios, we use the proposed WiMedia data rates requests defined in Table 1, and we consider the first WiMedia channel (3.1–4.7 GHz) for CM1 channel model.

5.2. Simulation Results. In this section, we present the simulation results for the proposed spectrum sharing scheme, and we compare the performance of the optimal solution with the proposed low-complexity suboptimal solution. The system performance will be evaluated in terms of time-frequency QoS satisfaction. Two metrics are thus considered for the QoS evaluation: one frequency metric related to the channel and rate satisfaction represented by the channel Satisfaction Index (SI), and another time metric representing the time delay of the scheduled users to assess the efficiency of the time-scheduling scheme. Moreover, we compare the performance of the proposed MB-OFDM-MA solution to the OFDMA scheme as well as to the single-user WiMedia solution.

5.2.1. Channel Satisfaction Index Comparison. For performance comparison purpose, we introduce a cross-layer performance metric called the Satisfaction Index (SI) defined as

$$\mathrm{SI}_k \frac{\mathrm{E}_{k,b}}{\max_b \mathrm{E}_{k,b}}. \tag{29}$$

This new evaluation metric is defined to reflect the cross-layer aspect of the proposed scheduling scheme. It evaluates the channel satisfaction level of a user k assigned a subband b by using the effective SINR value which is correlated to its BER and its effective data rate via parameter λ as given in Table 1. It will be equal to one if the user is fully satisfied since it is assigned its best subband. The SI is consequently a QoS parameter and can be used to evaluate the fairness among the users.

In Figure 4, we compare the user SI level obtained in the optimal and the suboptimal allocation functions given by (11) and (24), respectively, for different possible rates of the WiMedia solution. We consider a scenario consisting of three users aiming at sharing the three subbands of one WiMedia channel: one hard-QoS user requesting the highest data rate, that is 480 Mbps, and two soft-QoS users requesting data rates between 53.3 and 200 Mbps. While the SI of the hard-QoS user is equal to one in the optimal and suboptimal solutions since it is assigned its best subband in both cases, soft-QoS users SI varies according to their data rates. This is due to the fact that the users channel gain is represented by the effective SINR which depends on the data rate by means of parameter λ (see Table 1). Thus, we evaluate the performance of the highest and lowest priority users for the first five data rates. As shown in the figure, the suboptimal subband allocation solution with its low-complexity computation performs close to the iterative optimal solution; an average of 10% of outperformance is outlined for the sake of the optimal solution.

5.2.2. Time Delay Comparison. In Figure 5, we evaluate the QoS support in the proposed time-frequency sharing scheme

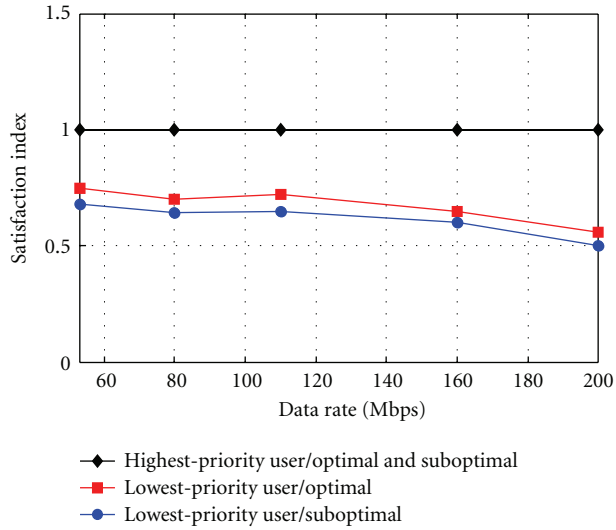

Figure 4: Satisfaction Index of the highest and lowest priority users in the optimal and suboptimal solutions.

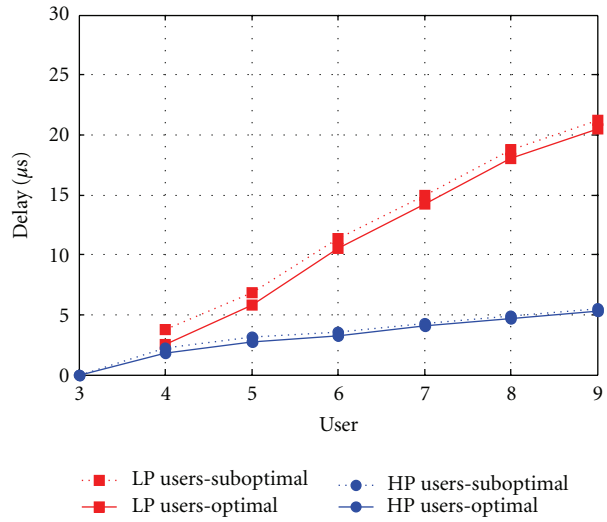

Figure 5: The delay of high-priority (HP) and low-priority (LP) users in a multiuser sharing scenario.

in terms of average delay per MAS duration. We consider thus the case of nine users aiming at sharing one superframe by using the proposed optimal and suboptimal spectrum sharing solutions. The nine users are requesting 480, 400, 320, 200, 160, 110, 80, 53.3, and 53.3 Mbps, respectively. The users are arranged according to their priority order and classified into HP and LP users. As shown in the figure, when the first three HP users share the spectrum, there is no delay since there is no time sharing. However, when the LP users time-share the spectrum with the HP users, the performance degrades and the delay increases. Nevertheless, we observe that the delay of the HP users is considerably less than the delay of the LP users in both optimal and suboptimal solutions. The QoS of the HP group is thus well guaranteed since the average of the sum of the delays of the HP users

is relatively low when nine users are sharing the same superframe. On the other hand, the delay in the LP group is more considerable. This can be tolerable when the services of this group are data or BE services, which have tolerance for delay. However, note that if the LP group consists of some hard-QoS users, the performance of these hard-QoS users will degrade and the QoS will not be ensured. Consequently, the ideal case is to have only three hard-QoS users forming the HP group and the other users are soft-QoS users.

Besides, it is noticed that the optimal and suboptimal solutions perform very close in the time-frequency sharing scheme especially in the case of HP users. This proves that the performance difference between optimal and suboptimal allocation functions is reduced in the time domain when combining the frequency allocation with the time scheduling.

5.2.3. Performance Comparison of the Proposed MB-OFDM-MA Solution with the OFDMA Scheme and the Single-User Wimedia MB-OFDM Solution. In order to assess the efficiency of the proposed MB-OFDM-MA spectrum sharing scheme, we compare its performance to two other schemes: the first one is the traditional OFDMA, which allocates subcarriers to users according to their channel power and the second one is the differentiated OFDMA (D-OFDMA), which takes into account the QoS support. The latter solution results from the application of our proposed QoS-aware resource allocation solution on OFDMA, that is using the cross-layer allocation function defined in (24). Moreover, we consider two versions of the proposed scheme: (i) the optimal solution without fairness provision and (ii) the suboptimal with fairness provision, that is using the WCR mechanism. In Figure 6, we evaluate the performance of three users transmitting simultaneously during one MAS duration in terms of average SI. The requested data rates of the users are 480, 200, and 53.3 Mbps, respectively. As shown in the figure, although the first two users are very well satisfied in the case of D-OFDMA and the optimal MB-OFDM-MA, the third user satisfaction level is relatively low. On the other hand, the OFDMA and the low-complexity WCR-MB-OFDM-MA perform almost the same and ensure a very good level of fairness among the three users. This is due to the subband permutation achieved in the WCR mechanism which allows the low-priority users to benefit from best channel qualities for a time proportional to their weights.

In Figure 7, we compare the performance of our suboptimal multiuser allocation solution to the single-user WiMedia solution. The plotted curves represent the E_b/N_0 required to reach a BER level of 10^{-4} for each of the WiMedia data rates. The same "nine-users" scenario considered in Figure 5 is used here. As shown in the figure, the highest priority user has a considerable gain compared to the lowest priority user. For example, at a data rate equal to 200 Mbps, the highest priority user outperforms the lowest priority user with a 2.3 dB gain. On the other hand, the lowest priority user performance is slightly degraded compared to the WiMedia solution. This proves that the fixed TFC as defined in the WiMedia solution does not give advantage to high-priority users that are privileged in the proposed multiuser spectrum sharing solution since the allocation is achieved proportionally to the users priorities.

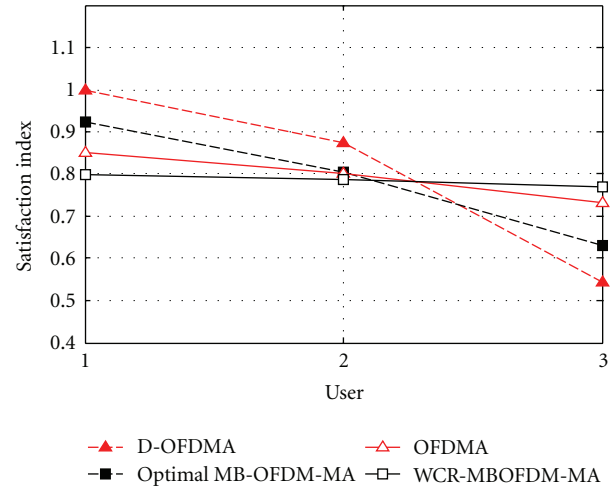

Figure 6: Comparison of the proposed MB-OFDM-MA solution with other multiuser schemes.

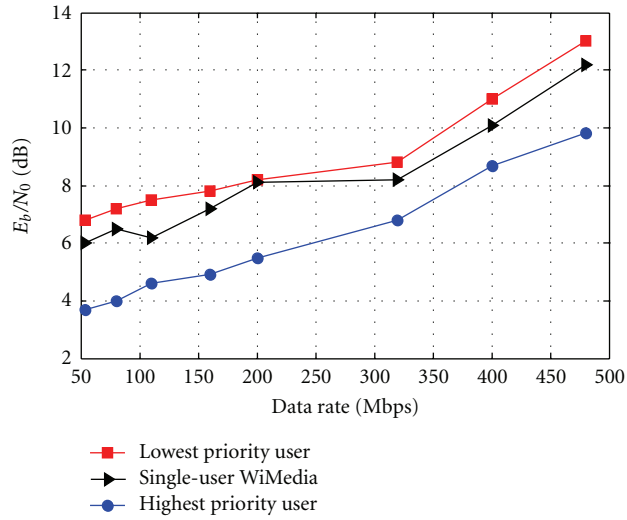

Figure 7: Performance of the highest and lowest priority users for the different WiMedia data rate modes.

6. Conclusion

In this paper, we have proposed a novel spectrum sharing scheme based on a cross-layer MB-OFDM-MA approach. This new scheme has considered both the frequency resource allocation and the time scheduling issues by deriving a joint optimization model resulting in an MB-OFDM time-frequency spectrum sharing scheme. However, to reduce the complexity of the optimal spectrum sharing solution, a low-complexity suboptimal spectrum sharing model has been proposed based on suboptimal resource allocation and scheduling solutions. The low-complexity time-frequency spectrum sharing solution takes into account the fairness provision jointly with the QoS support. It uses a mechanism

that interchanges the priority among the users by offering them the opportunity to choose their best-quality channels during a fraction of the superframe proportionally to their priority weights. Combined with the priority-based time-frequency sharing approach, the fair scheduling mechanism ensures a good level of fairness among the users while respecting the concept of prioritization among them. Compared with the single-user WiMedia solution and the high-complexity OFDMA scheme, the low-complexity MB-OFDM-MA can be a solution for the multiuser medium access problem in WiMedia UWB systems as well as in next generation OFDM systems.

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References

[1] J. Moon, J. Y. Ko, and Y. H. Lee, "A framework design for the next-generation radio access system," *IEEE Journal on Selected Areas in Communications*, vol. 24, no. 3, pp. 554–564, 2006.

[2] J. Jang and K. B. Lee, "Transmit power adaptation for multiuser OFDM systems," *IEEE Journal on Selected Areas in Communications*, vol. 21, no. 2, pp. 171–178, 2003.

[3] C. Y. Wong, R. S. Cheng, K. B. Letaief, and R. D. Murch, "Multiuser OFDM with adaptive subcarrier, bit, and power allocation," *IEEE Journal on Selected Areas in Communications*, vol. 17, no. 10, pp. 1747–1758, 1999.

[4] I. Kim, I. S. Park, and Y. H. Lee, "Use of linear programming for dynamic subcarrier and bit allocation in multiuser OFDM," *IEEE Transactions on Vehicular Technology*, vol. 55, no. 4, pp. 1195–1207, 2006.

[5] Y. Shang and S. Cheng, "An enhanced packet scheduling algorithm for QoS support in IEEE 802.16 wireless network," in *Proceedings of the International Conference on Communications, Networking and Mobile Computing (ICCNMC '05)*, vol. 3619 of *Lecture Notes in Computer Science*, pp. 652–661, Zhangjiajie, China, August 2005.

[6] V. Singh and V. Sharma, "Efficient and fair scheduling of uplink and downlink in IEEE 802.16 OFDMA networks," in *Proceedings of the IEEE Wireless Communications and Networking Conference (WCNC '06)*, vol. 2, pp. 984–990, April 2006.

[7] L. Badia, A. Baiocchi, A. Todini et al., "On the impact of physical layer awareness on scheduling and resource allocation in broadband multicellular IEEE 802.16 systems," *IEEE Wireless Communications*, vol. 14, no. 1, pp. 36–43, 2007.

[8] WiMedia Alliance, Inc., "Multi-band OFDM physical layer specification," Release 1.1, July 2005.

[9] A. Batra, J. Balakrishnan, G. R. Aiello, J. R. Foerster, and A. Dabak, "Design of a multiband OFDM system for realistic UWB channel environments," *IEEE Transactions on Microwave Theory and Techniques*, vol. 52, no. 9 I, pp. 2123–2138, 2004.

[10] Z. Chen, D. Wang, and G. Ding, "An OFDM-UWB scheme with adaptive carrier selection and power allocation," in *Proceedings of the International Conference on Wireless Communications, Networking and Mobile Computing (WiCOM '06)*, pp. 1–4, Wuhan, China, September 2006.

[11] J. Wang, G. Zhu, and J. Jin, "Optimal power allocation for space-time coded OFDM UWB systems," in *Proceedings of the International Conference on Wireless Communications, Networking and Mobile Computing (WCNM '05)*, vol. 1, pp. 169–172, September 2005.

[12] Z. Xu and L. Liu, "Power allocation for multi-band OFDM UWB communication networks," in *Proceedings of the 60th IEEE Vehicular Technology Conference (VTC '04)*, pp. 368–372, Los Angeles, Calif, USA, September 2004.

[13] W. P. Siriwongpairat, Z. Han, and K. J. R. Liu, "Power controlled channel allocation for multiuser multiband UWB systems," *IEEE Transactions on Wireless Communications*, vol. 6, no. 2, pp. 583–592, 2007.

[14] A. Khalil, M. Crussière, and J. F. Hélard, "Differentiated multiuser resource allocation scheme for multi-band UWB systems," in *Proceedings of the 10th IEEE Workshop on Signal Processing Advances in Wireless Communications (SPAWC '09)*, pp. 707–711, Perugia, Italy, June 2009.

[15] 15. 3GPP TSG-RAN-1, "R1-030999: considerations on the system performance evaluation of HSDP using OFDM modulations," RAN WG1 #34.

[16] J. Foester, "Channel modeling sub-committee report (final)," IEEE P802.15.-02/490rl-SG3a, 2003.

[17] A. A. M. Saleh and R. A. Valenzuela, "A statistical model for indoor multipath propagation," *IEEE Journal on Selected Areas in Communications*, vol. 5, no. 2, pp. 128–137, 1987.