Multiuser Service Differentiated Spectrum Allocation Scheme for High Rate UWB Systems

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Abstract— **In this paper, we propose a multiuser spectrum allocation scheme for high-rate UWB systems under QoS requirements. This scheme comes as a solution to the coexistence of multiple users sharing the three sub-bands of the same channel as defined in the WiMedia solution adopted for multiband UWB systems. Indeed, WiMedia solution does not allow more than three users to coexist in the same channel. Based on a constrained multiuser optimization problem, the proposed allocation algorithm allows multiple users to access the medium following a mixed sub-band assignment and priority-based scheduling approach in order to ensure an efficient differentiated spectrum sharing. The resulting time-frequency scheduling algorithm relies on the combination of two main metrics available at PHY and MAC levels: the channel quality of each user provided by the exploitation of the effective SINR method, and the QoS constraint represented by a simple weighting parameter that differentiates between two service classes. Simulation results show the efficiency of the proposed scheme and how it guarantees a good performance level for users having strict QoS requirements.**

Keywords- ***UWB; effective SINR; QoS; cross-layer.***

I. INTRODUCTION

Ultra-wideband (UWB) is a wireless transmission technology that has been growing industry wide interest during the last decade. UWB is interesting because of its inherent low power consumption, high data rates of up to 480 Mbit/s, and large spatial capacity. Furthermore, the power spectral density is low enough to prevent interference with other wireless services. This new technology has been approved by the Federal Communications Commission in 2002 for unlicensed use over the 3.1 – 10.6 GHz bands with an imposed power spectral density limit of -41.3 dBm/MHz [1]. So far, two competing physical layer specifications are currently available: one based on direct sequence spread spectrum (DS-UWB), and the other based on multiband orthogonal frequency division multiplexing (MB-OFDM). In this article, we focus on the latter scheme which is supported by the WiMedia Alliance [2] and has been standardized by ECMA [3].

One of the main topics of interest in UWB systems is the multiuser medium access management. This task is all the more challenging than UWB systems are based on a distributed network architecture where no device acts as a coordinator. To this date, most of the allocation studies that address the resource allocation issue in MB-OFDM systems do not take into consideration the quality of service (QoS) and the traffic differentiation matter in the multiuser environment. In [4] and [5] for example, resource allocation solutions are investigated but in the unique case of single-user MB-OFDM systems. On the other hand, the authors in [6] consider the multiuser context but without taking into consideration the users QoS requirements.

In this work, we investigate the problem of resource allocation and spectrum sharing in MB-OFDM with the aim of proposing an efficient algorithm that allows a satisfactory number of users, i.e. more than three users, to coexist while responding to each user QoS constraints. At first, the optimal allocation solution is obtained by deriving the adequate multiuser optimization problem. From this analytical study, we then propose a simple multiuser allocation scheme based on priority principles and following a time-frequency scheduling approach. Consequently, the proposed algorithm renders possible the coexistence of multiple users in the same three sub-bands of one WiMedia channel. In order to differentiate between the existing users, we define two service classes: hard-QoS (H-QoS) for real-time applications (voice, video), and soft-QoS (S-QoS) for non real-time applications (best effort and background). On the other hand, our algorithm exploits channel information provided by the so-called effective SINR method [7]. Combined in a simple and efficient way, these service MAC condition and channel PHY information metrics are eventually used for the scheduling and the multiple access management.

The remainder of this paper is organized as follows. Section II introduces the system model. Section III derives the multiuser optimization problem and presents the optimal solution. Based on that solution, we propose in section IV a simplified time-frequency scheduling algorithm. Section V presents simulation results showing the efficiency of the proposed scheme, and the performance of the multiuser solution compared to the single user WiMedia solution. Finally, section VI concludes this paper.

II. SYSTEM MODEL

The WiMedia PHY is designed to achieve data rates of up to 480 Mbit/s per user. Between 3.1 GHz and 10.6 GHz five band groups are defined. Support of band group 1 is mandatory. Support for all others is optional. Except for the highest band group, all groups consist of three frequency bands

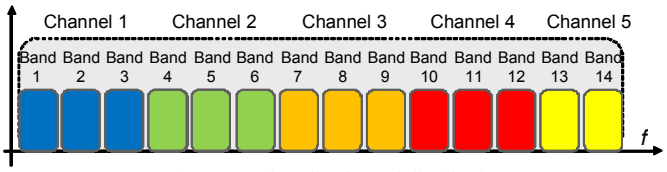

Figure 1. WiMedia channel distribution.

as shown in Fig.1. One frequency band in WiMedia is 528 MHz wide and is divided into 128 OFDM subcarriers, 100 out of them are used for data. Time frequency codes (TFC) in conjunction with the 5 frequency band groups are used. Each TFC provides a hopping sequence applied to a band group.

The constellation applied to the subcarriers is either the quadrature phase-shift keying (QPSK) for the first five rate modes, or the dual carrier modulation (DCM) for the highest three data rates. Table I gives the details concerning the data rate, modulation and coding rate for each WiMedia PHY mode.

The WiMedia MAC is based on distributed control [2]. This means that the MAC layer does not define any device to be an access point, but instead all devices have equal responsibilities and equal rights for gaining access to the TDMA channel. For the medium access, WiMedia introduces the so-called prioritized channel access (PCA) and distributed reservation protocol (DRP). While the former is well known from the enhanced distributed channel access (EDCA) used in IEEE802.11e, the latter is based on an advanced reservation scheme ensuring collision-free access to the channel. None of these access mechanisms are actually used to jointly address the QoS issue and solve the collision problem.

In the sequel, we propose to combine reservation and negotiation principles provided by DRP with the proposed QoS-constrained allocation algorithm. Hereby, it is expected to obtain an efficient access mechanism for the WiMedia system that gives satisfaction to each user conditions.

III. Problem Formulation

A. Service Differentiation parameter

It is proposed to classify the UWB service types into two classes: hard-QoS (H-QoS) class for services that have strict QoS requirements (voice, video) and soft-QoS (S-QoS) class for services that have tolerance for some requirements (BE, background). To represent this service differentiation, we define for each user k a QoS priority level PL. This PL definition has to ensure two differentiation levels: the class level where an H-QoS user should have a considerable advantage on an S-QoS user, and the service level where two services that belong to the same class have to be differentiated according to their different data rate requirements. The PL is thus a combination of the class weight and the data rate requirements and is defined as follows

$$PL_k = q_k r_k \tag{1}$$

where

$$\begin{cases} q_k = 1 & \text{for S-QoS users} \\ q_k = 2 & \text{for H-QoS users} \end{cases} \tag{2}$$

TABLE I. WiMedia System Data Rates

Data Rate (Mbit/s)	Modulation	Coding Rate	FDS	TDS	λ
53.3	QPSK	1/3	Yes	Yes	**1.49**
80	QPSK	1/2	Yes	Yes	**1.57**
110	QPSK	11/32	No	Yes	**1.52**
160	QPSK	1/2	No	Yes	**1.57**
200	QPSK	5/8	No	No	**1.82**
320	DCM	1/2	No	No	**1.85**
400	DCM	5/8	No	No	**1.82**
480	DCM	3/4	No	No	**1.80**

and,

$$r_k = 1 + \frac{R_k - R_{\min}}{R_{\max} - R_{\min}} \tag{3}$$

where R_k, R_{min} and R_{max} are the requested rate of user k, the lowest and highest data rates taken from WiMedia modes (see Table I), respectively.

B. Channel Quality parameter

Assuming that the instantaneous SINR for each subcarrier is known by each user, namely resulting from classical channel estimation operations for example, it is possible to get an evaluation of the system level performance in terms of BER by using the effective SINR approach [7]. This method consists in finding a compression function that is able to represent the characteristics of each sub-band by mapping the sequence of varying SINRs to a single value that is correlated with the actual BER [8]. It is given by

$$SINR_{eff} = -\lambda \ln\left[\frac{1}{N}\sum_{i=1}^{N}\exp(-\frac{SINR_i}{\lambda})\right] \tag{4}$$

where N is the number of subcarriers in a sub-band, $SINR_i$ the ratio of signal to interference and noise for the i^{th} subcarrier and λ is a scaling factor that depends on the selected modulation and coding scheme (MCS). λ is computed and evaluated for the eight WiMedia data rate modes as shown in Table I. In the following the effective SINR will be used as a metric providing the channel information for each user.

C. Problem Formulation

We consider a system consisting of K UWB users where the first K_h users are H-QoS users and the remaining $K - K_h$ are S-QoS users. The rate of a user k in sub-band b is defined as

$$r_{k,b} = \log_2(1 + P_{k,b}\xi_{k,b}) \tag{5}$$

where $P_{k,b}$ is the allocated power of user k in sub-band b, and $\xi_{k,b}$ is the effective SINR of user k in this sub-band. The goal is to optimize the sub-band allocation under the total power constraint P_T so as to maximize the total data rate of the $K - K_h$ S-QoS users while maintaining a certain level of transmission rate for the K_h H-QoS users. The problem can hence be stated as

$$\max_{S_k} \quad \sum_{k=K_h+1}^{K} \sum_{b \in S_k} r_{k,b}$$
$$s.t. \quad \sum_{b \in S_k} r_{k,b} \geq R_k, \quad k = 1,...,K_h \qquad (6)$$
$$\sum_{k=1}^{K} \sum_{b=1}^{B} P_{k,b} \leq P_T$$

where B is the total number of sub-bands, R_k the H-QoS users 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. Adopting a new parameter $\omega_{k,b}$, we can convert this problem into a convex optimization problem [9]. This parameter represents a time-sharing factor for the user k of the sub-band b. The optimization problem can then be reformulated as

$$\max_{P_{k,b},\omega_{k,b}} \quad \sum_{k=K_h+1}^{K} \sum_{b=1}^{B} \omega_{k,b} \log_2(1+\frac{P_{k,b}\xi_{k,b}}{\omega_{k,b}})$$
$$s.t. \quad \sum_{b=1}^{B} \omega_{k,b} \log_2(1+\frac{P_{k,b}\xi_{k,b}}{\omega_{k,b}}) \geq R_k, \quad k = 1,...,K_h \qquad (7)$$
$$\sum_{k=1}^{K} \omega_{k,b} = 1 \quad \forall b \qquad 0 \leq \omega_{k,b} \leq 1 \quad \forall k,b$$
$$\sum_{k=1}^{K} \sum_{b=1}^{B} P_{k,b} \leq P_T$$

which turns out to be a convex maximization problem. Using standard optimization techniques, we obtain the Lagrangian

$$L = \sum_{k=K_h+1}^{K} \sum_{b=1}^{B} \omega_{k,b} \log_2(1+\frac{P_{k,b}\xi_{k,b}}{\omega_{k,b}}) + \sum_{k=1}^{K_h} \alpha_k \left(\sum_{b=1}^{B} \omega_{k,b} \log_2(1+\frac{P_{k,b}\xi_{k,b}}{\omega_{k,b}}) - R_k\right)$$
$$+ \sum_{b=1}^{B} \beta_b (1 - \sum_{k=1}^{K} \omega_{k,b}) + \gamma(P_T - \sum_{k=1}^{K} \sum_{b=1}^{B} P_{k,b}) \qquad (8)$$

Let $P^*_{k,b}$ and $\omega^*_{k,b}$ be the optimal solution. After differentiating (8) with respect to $P_{k,b}$ and $\omega_{k,b}$ respectively by KKT optimality condition, we obtain

$$\alpha_k \left[\log_2(\frac{\alpha_k \xi_{k,b}}{\gamma \ln 2}) - \frac{1}{\ln 2}(1 - \frac{\gamma \ln 2}{\alpha_k \xi_{k,b}}) \right] - \beta_b = 0 \text{ for } k = 1,..,K_h$$
$$\log_2(\frac{\xi_{k,b}}{\gamma \ln 2}) - \frac{1}{\ln 2}(1 - \frac{\gamma \ln 2}{\xi_{k,b}}) - \beta_b = 0 \qquad \text{for } k = K_h+1,..,K \quad (9)$$

Since $\omega^*_{k,b}$ should satisfy the following KKT conditions:

$$\frac{\partial L}{\partial \omega^*_{k,b}} = \begin{cases} >0 & \omega^*_{k,b} = 1 \\ = 0 & \omega^*_{k,b} \in]0,1[\\ < 0 & \omega^*_{k,b} = 0 \end{cases} \qquad (10)$$

Substituting (9) into (10), we get

$$\omega^*_{k,b} = \begin{cases} 1 & I_{k,b} > \beta_b \\ 0 & I_{k,b} < \beta_b \end{cases} \qquad (11)$$

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

$$I_{k,b} = \alpha_k \left[\log_2(\frac{\alpha_k \xi_{k,b}}{\gamma \ln 2}) - \frac{1}{\ln 2}(1 - \frac{\gamma \ln 2}{\alpha_k \xi_{k,b}}) \right] \quad \text{for } k = 1,..,K_h$$
$$I_{k,b} = \log_2(\frac{\xi_{k,b}}{\gamma \ln 2}) - \frac{1}{\ln 2}(1 - \frac{\gamma \ln 2}{\xi_{k,b}}) \qquad \text{for } k = K_h+1,..,K \quad (12)$$

We conclude that, for a selected sub-band, the user with the largest $I_{k,b}$ can use this sub-band. In other words, for a sub-band b, if $I_{k,b}$ are different for all k, then

$$\omega^*_{k',b} = 1, \quad \omega^*_{k,b} = 0 \quad \text{for all } k \neq k' \qquad (13)$$

where,

$$k' = \arg\max_k I_{k,b} \qquad (14)$$

In order to compute $I_{k,b}$ for all users, we need to find the set of α_k such that the H-QoS rate constraints are satisfied. Thus, an iterative searching algorithm is needed; starting with small values of α_k and then increasing them iteratively until the data rate for all H-QoS users are satisfied. However, this iterative solution requires an intensive computation cost. Therefore, we propose a suboptimal solution based on a simple cross-layer approach in the next section.

IV. Proposed Scheme

By analyzing the optimal solution obtained in the previous section, we note that the allocation function given by (12) has the following characteristics: (i) the function is monotonically increasing with respect to $\xi_{k,b}$ and, (ii) the function is monotonically increasing with respect to α_k for the H-QoS users. In other terms, the function depends on the user priority and thus, the stricter the user requirements, the higher the value of this function. Taking into account these characteristics, we define a suboptimal allocation function based on a cross-layer approach in combining information provided by PHY and MAC layers. The idea is to replace α_k by a static parameter that could be defined once by all the users. We propose thus to use the *PL* (or the service differentiation) parameter defined in section III.A. This can be justified by the fact that the *PL* parameter has the same characteristics as α_k; both parameters depend on the service requirements or QoS level. The proposed allocation function is thus defined by

$$\tilde{I}_{k,b} = PL_k \xi_{k,b} \qquad (15)$$

This function, viewed as a suboptimal solution, combines in a simple way the channel information through the exploitation of the $\xi_{k,b}$ value, with the user priority level through the use of the priority level function given by (1).

Based on this cross-layer function, we define a multiuser sub-band allocation algorithm that describes all the allocation steps. Indeed, in our system which consists of three sub-bands in one channel, we consider two cases: the case of less than three users ($K \leq 3$) in one channel using a simple frequency

sharing approach, and the case of more than three users (K > 3) in one channel using a time-frequency sharing approach.

The different steps of the algorithm are depicted by the flowchart in Fig. 2. As illustrated, the case of $K \leq 3$ is a pure priority-based case, where we assign one sub-band to each user according to its $\tilde{I}_{k,b}$ value.

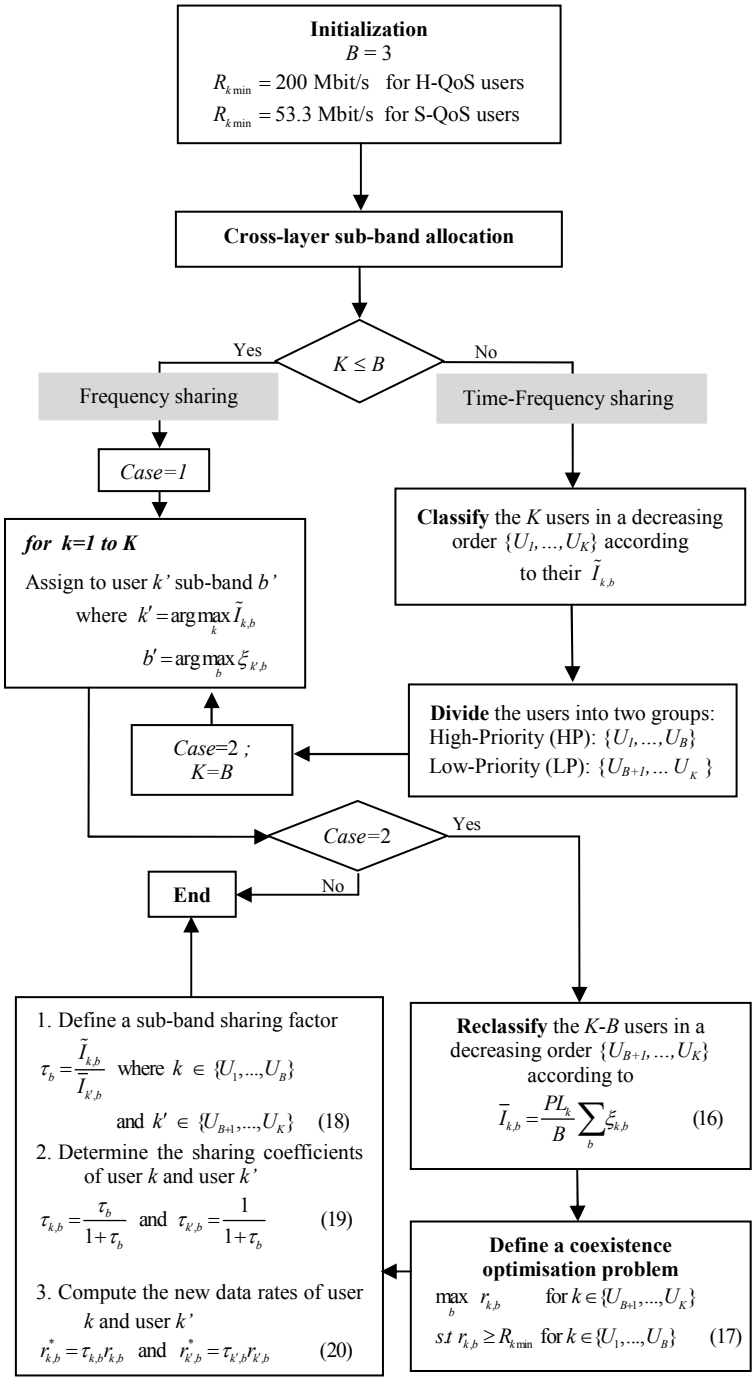

Figure 2. Flow chart of the proposed scheme.

On the other hand, when K > 3, time sharing is added to frequency sharing in order to allow more than three users to coexist in the same channel. Besides, a priority-based scheduling is also followed, but using a different approach than in the case of $K \leq 3$. More precisely, the K existing users are first classified in a decreasing order according to their $\tilde{I}_{k,b}$ values. Denoting B the number of sub-bands (B=3 in our case), the first B users with the highest $\tilde{I}_{k,b}$ values are assigned the available B sub-bands in the same way as in the case of $K \leq 3$. Then, the remaining $K - B$ users aim at accessing the sub-bands already allocated to the first B users through time sharing. Therefore, these $K - B$ users are reclassified according to a new $\bar{I}_{k,b}$ value which is the mean of the $\tilde{I}_{k,b}$ of each user over the B sub-bands. This modified metric is justified by the fact that these $K - B$ users do not have any assigned sub-band yet since all the available sub-bands have already been assigned.

So far, we have a new user classification: the High-Priority (HP) B users, and the Low-Priority (LP) $K - B$ users. The objective is to allow the LP users to coexist with the HP users in an efficient time sharing way that respects all the QoS constraints.

In other terms, for each LP user, we should find the corresponding sub-band b that maximizes its rate while minimizing the loss of rate of the HP user already assigned this sub-band b. We then introduce a sharing factor τ_b in (18) that represents the spectrum utilization advantage of a HP user on a LP user. Indeed, a HP user should have a data rate greater than that of a LP user by a factor τ_b. As a result, the allocation of the $K - B$ users is performed in a priority order: the highest priority user from these $K - B$ users chooses first the sub-band or equivalently the user from the B already allocated users to time-share spectrum with. To do so, that user makes an exhaustive search to find the sub-band that responds to (17) by using (19) and (20). We repeat the process until all of the $K - B$ users are assigned. Note that time sharing allows in principle a large number of users to coexist. However, we will consider here that at most two users can share the same sub-band in time in order not to decrease the performance significantly. As a result, up to K=6 users can coexist in one WiMedia channel.

V. System Performance

A. Channel Model

The channel used in this study is the one adopted by the IEEE 802.15.3a committee for the evaluation of UWB physical layer proposals. This model is a modified version of Saleh-Valenzuela model for indoor channels [10], fitting the properties of UWB channels. A log-normal distribution is used for the multipath gain magnitude. Also, independent fading is assumed for each cluster and each ray within the cluster.

Four different channel models (CM1 to CM4) are defined for the UWB system modeling, 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.

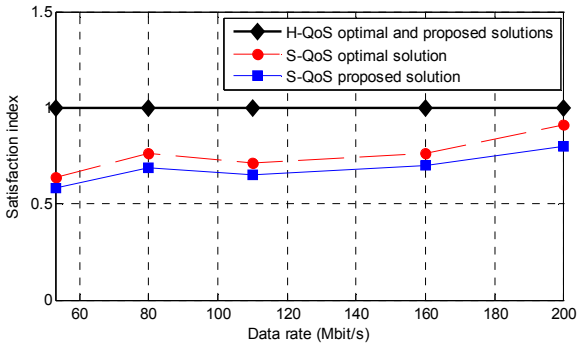

Figure 3. Satisfaction level of users in different WiMedia data rates.

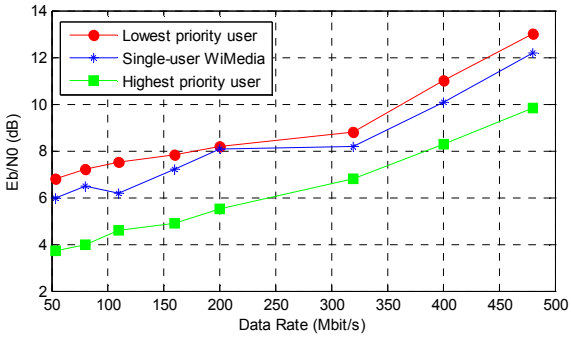

Figure 4. Performance of the highest and lowest priority users in the different WiMedia data rates.

B. *Simulation Results*

In this section, we present the simulation results for the proposed multiuser cross-layer allocation scheme and we compare the performance of the new scheme with that of the optimal solution as well as the single-user WiMedia solution using TFC. Therefore, we use the proposed WiMedia data rates (see Table I). The results are performed on the first three WiMedia sub-bands (3.1- 4.7 GHz) for CM1 channel model.

To have fair comparisons, we introduce a user satisfaction index η_k as being the ratio between the effective SINR of the sub-band assigned to user k and the best of the effective SINRs across the B sub-bands of the same user. This is expressed as:

$$\eta_k = \frac{\tilde{\xi}_{k,b}}{\max_b(\xi_{k,b})} \qquad (21)$$

In Fig. 3, we compare the user satisfaction levels obtained in the optimal and the cross-layer simplified algorithms. We consider a three users scenario: one H-QoS user and two S-QoS users. While the satisfaction index for the H-QoS user is equal to one in the optimal and cross-layer solutions since it is assigned its best sub-band in both cases, S-QoS users satisfaction index varies according to their data rates. This is due to the fact that the power of users is represented by the effective SINR which depends on the data rate by means of λ parameter (see Table I). We assume that S-QoS users data rate is limited to 200 Mbit/s. Thus, we evaluate the performance of the different users in the first five data rates. As shown in the figure, the performance of the cross-layer solution is close to that of the optimal solution previously defined. Note that this result does not change in the six users case since the same sub-bands will be shared among all the existing users.

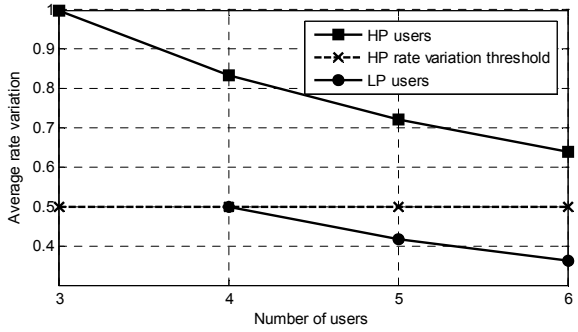

Figure 5. Average rate variation of HP and LP users in a six users scenario.

In Fig. 4, a six users scenario is considered and the performance is evaluated for the eight WiMedia data rate modes, i.e. from 53 to 480 Mbit/s. The plotted curves represent the E_b / N_0 required to reach a $BER = 10^{-4}$ for each of the data rates. The users are classified in a priority order where the highest priority user is the one having the highest $\tilde{I}_{k,b}$ value. 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 Mbit/s, 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 performance degradation of the low-priority users (or the S-QoS users) can be viewed as a sacrifice for the sake of the high-priority users (or H-QoS users) to ensure their strict QoS requirements.

In Fig. 5, we present the performance degradation, particularly the rate variation of the existing users in the case of a six users case. Here, the users are classified according to their priority order and the rate variation is defined as

$$\Delta R = \frac{allocated\ data\ rate}{required\ data\ rate} \qquad (22)$$

It actually represents the rate satisfaction of each user. We can observe that a user rate is degraded proportionally to its priority level, i.e. more the user priority is low, more its performance is degraded. Besides, since the HP users have a guaranteed minimum rate level represented by $R_{k\min}$ in (17), we have to verify that their performance is never degraded significantly and their QoS requirements are satisfied. Thus, we define a high-priority rate variation threshold as

$$\Delta R_{thres} = \frac{R_{k\min}}{required\ data\ rate} \qquad (23)$$

We consider here that all the HP users have the same required data rate of 400 Mbit/s and that the value of $R_{k\min}$ is equal to 200 Mbit/s. As shown in the figure, the HP users performance responds to their rate constraint and the threshold is always respected. Note the performance degradation of the LP users is

tolerable since these users have lesser requirements in terms of data rate.

VI. Conclusion

In this paper, we proposed a solution for the multiuser resource allocation under QoS requirements in UWB systems. This solution is based on a time-frequency spectrum sharing scheme which takes into consideration the channel conditions and the users QoS constraints. Based on an optimal analytical allocation solution, we proposed a simplified cross-layer approach which combines the user QoS requirements (priority level) and the user channel power (effective SINR) in a simple and efficient function. This priority-based cross-layer approach offers a solution for the coexistence of more than three users in the same WiMedia channel while respecting each user nature and requirements. Finally, we showed through simulations that the proposed scheme performance is close to the optimal solution performance. Moreover, simulations showed that the cross-layer multiuser solution enhances the performance of the H-QoS users while not decreasing significantly the performance of the S-QoS users.

Acknowledgment

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References

[1] "First report and order, revision of part 15 of the commission's rules regarding ultra-wideband transmission systems," FCC, ET Docket 98-153, Feb. 14, 2002.

[2] WiMedia Alliance, Inc., "Multiband OFDM physical layer specification," Release 1.1, July 2005.

[3] Standard ECMA-368, High rate ultra wideband PHY and MAC standard, 2nd edition, Sept. 2007.

[4] Z. Chen, D. Wang and G. Ding, "An OFDM-UWB Scheme with Adaptive Carrier Selection and Power Allocation," in *Proc. IEEE Intern. Conference on Wireless Communications, Networking and Mobile Computing (WiCOM '06)*, pp.1–4, China, Sept. 2006.

[5] A. Stephan, J-Y. Baudais and J-F. Helard, "Efficient Allocation Algorithms for Multicarrier Spread Spectrum schemes in UWB applications," in *Proc. IEEE Intern. Conference on Ultra-Wideband (ICUWB '07)*, pp. 551–555, Singapore, Sept. 2007.

[6] W.P Siriwongpairat, Z. Han and K. J Ray Liu, "Power controlled channel allocation for multi-user multiband UWB systems," *IEEE Trans. Wireless Communications,* vol. 6, no. 2, pp. 583–592, Feb. 2007.

[7] 3GPP TSG-RAN-1, "R1-030999: considerations on the system-performance evaluation of HSDP using OFDM modulations"; RAN WG1 #34.

[8] R. Yaniv, D. Stopler, T. Kaitz, K. Blum, "CINR Measurements using the EESM Method," IEEE 802.16e Contribution #141 revision 1, 2005.

[9] P. W. C. Chan and R. S. Cheng, "Optimal power allocation in zero-forcing MIMO-OFDM downlink with multiuser diversity," in *Proc. of IST Mobile & Wireless Communications Summit*, Dresden, June 2005.

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