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Ayman Khalil, Antoine Stephan, Matthieu Crussière, Jean-François Hérald. Multi-user cross-layer allocation design for LP-OFDM high-rate UWB. International Symposium for Wireless Communication Systems, Oct 2008, Reykjavik, Iceland. pp.1-5, 10.1109/ISWCS.2008.4726007 . hal-00325637

HAL Id: hal-00325637

<https://hal.science/hal-00325637>

Submitted on 2 Dec 2008

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Multi-user Cross-layer Allocation Design for LP-OFDM High Data Rate UWB Systems

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Abstract—In this paper, we investigate a cross-layer design for the packet scheduling and the resource allocation in UWB systems. This design considers the combination of queuing and channel state information (CSI) which provides QoS support for multimedia applications in UWB. For the physical layer, the use of a linear precoded orthogonal division multiplexing (LP-OFDM) waveform is proposed because of its significant performance increase compared to the WiMedia proposal. For the medium access control layer, scheduling is performed in order to differentiate between the different users and to satisfy their quality of service constraints. This cross-layer approach optimizes the system spectral efficiency and solves the problem in the WiMedia solution of cohabitation of more than three users sharing the three sub-bands of the same channel. Simulation results show that the proposed scheme leads to a considerable improvement in resource allocation and can guarantee the required quality of service.

I. INTRODUCTION

Ultra-wideband transmission is an emerging technology for future high-rate, short-range wireless communications. Its wide bandwidth and low transmission power density make it attractive to researchers since 2002 when the Federal Communications Commission (FCC) regulated UWB systems by allocating the 3.1 to 10.6 GHz spectrum for unlicensed use of UWB [1]. In order to reduce interference with other existing systems, the FCC imposed a power spectral density (PSD) limit of -41.3 dBm/MHz.

The IEEE 802.15a wireless personal area networks (WPAN) standardization group defined a very high data rate physical layer based on UWB signalling. One of the multiple-access techniques considered by the group is a multiband orthogonal frequency division multiplexing (MB-OFDM) supported by the MultiBand OFDM Alliance (MBOA) and the WiMedia forum [2], [3], which merged in March 2005 and are today known as the WiMedia Alliance.

There have been a lot of studies on the resource allocation in UWB system based on the WiMedia solution. However, to this date, most research studies on multiband UWB systems have been devoted to the physical layer issues. In [4]–[6], the authors propose different sub-band and power allocation strategies based on the channel information without taking into account the users requirements and the quality of service issues. On the other hand, in [7], [8], the authors propose scheduling and power allocation algorithms that provide

quality of service for multimedia applications in UWB systems but without having a full knowledge of the channel.

The purpose of this paper is to propose a cross-layer resource management based on UWB signalling in a multi-user context. The proposed scheme jointly exploits scheduling and sub-band allocation principles to maintain an efficient use of the spectrum in a multiple medium access demand. In addition, we consider a physical layer based on a linear-precoded OFDM transmission scheme (LP-OFDM) also known as spread spectrum multicarrier multiple-access (SS-MC-MA) in the wireless context [9]. Based on this scheme, we shall consider the effect of the source statistics and scheduling in addition to the channel information provided by the physical layer model. Therefore, we need the contribution of the MAC layer for better QoS and higher utilization. A packet scheduler is defined by the MAC layer in order to control each user requirements, to manage the cohabitation of more than three users in one channel and to differentiate between two major traffic classes: real-time or Quality of Service (QoS), and non real-time or Best Effort (BE). The definition of these two classes is useful for UWB systems, where multimedia or real-time applications (video recording, A/V conferencing, etc) should have a certain priority on data or non real-time applications (file transfer, wireless USB, etc).

The remainder of this paper is organized as follows. Section II introduces the system model by presenting the physical and MAC layers conditions. Section III presents the proposed scheme that reflects the new concept of allocating the resources based on a cross-layer strategy. Section IV presents some simulations showing the efficiency and the good performance of the new scheme and its interest for UWB systems. Finally, section V concludes this paper.

II. SYSTEM MODEL

A. Physical Layer

1) *The WiMedia Solution*: The WiMedia solution consists of combining OFDM with a multi-banding technique that divides the available band into 14 sub-bands of 528 MHz, as illustrated in Fig. 1. An OFDM signal can be transmitted on each sub-band using a 128-point inverse fast Fourier transform (IFFT). Out of the 128 subcarriers used, only 100 are assigned to transmit data.

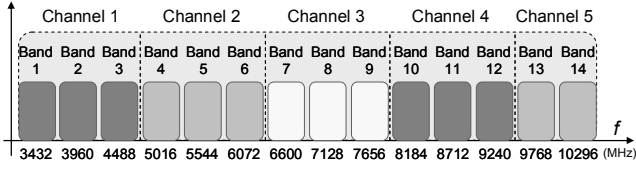


Fig. 1. Channel distribution for WiMedia solution

Different data rates from 53.3 to 480 Mbit/s are obtained through the use of forward error correction (FEC), frequency-domain spreading (FDS) and time-domain spreading (TDS). The constellation applied to the different subcarriers is either a quadrature phase-shift keying (QPSK) for the low data rates or a Dual Carrier Modulation (DCM) for the high data rates. Time-frequency codes (TFC) are used to provide frequency hopping from a sub-band to another at the end of each OFDM symbol. TFC allows every user to benefit from frequency diversity over a bandwidth equal to the three sub-bands of one channel. In WiMedia, there is no clear solution for simultaneous transmissions using TFC and conflicts between users appear when a fourth user is added in one channel.

2) *LP-OFDM System*: The LP-OFDM scheme is applied to UWB while respecting the OFDM parameters of the WiMedia solution. The system evolution reduces in practice to a simple addition of a precoding block in the transmission chain. Taking into account the frequency selectivity and the slow-time variations of the UWB channel in an indoor environment, the spreading sequences are applied in the frequency domain. This spreading component improves the signal robustness against frequency selectivity and narrowband interference, since the signal bandwidth becomes much larger than the coherence and interference bandwidths. Moreover, it increases the resource allocation flexibility as the spreading code dimension offers an additional degree of freedom [10]. We will assume that orthogonal spreading sequences are used in the proposed system.

A schematic representation of the LP-OFDM signal is illustrated in Fig. 2. At a given time, each user is allocated one of the first three WiMedia sub-bands of 528 MHz bandwidth each, in order not to increase the system complexity compared to the WiMedia solution. Each sub-band is then divided into several blocks, each of them including a number of subcarriers equal to the spreading code length L .

In a general approach, the generated symbol vector at the output of the OFDM modulator for an LP-OFDM system can be written as

$$s = F^H M X. \quad (1)$$

Vector s is N -dimensional, with N the number of used subcarriers. $X = [x_1, \dots, x_k]^T$ is the output of the serial-to-parallel conversion of the K QPSK-mapped symbols to be transmitted. M represents the $N \times K$ precoding matrix applied to X , which precodes K symbols over the N subcarriers. Finally, F^H represents the Hermitian of the $N \times N$ unitary Fourier matrix that realizes the multicarrier modulation.

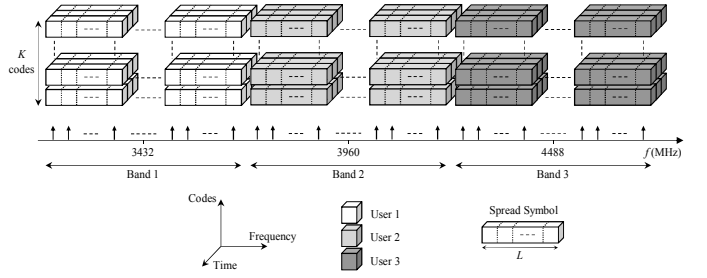


Fig. 2. LP-OFDM schematic representation for three users occupying the first three sub-bands of the WiMedia solution

Note that for simplicity reasons, (1) does not involve any guard interval contribution even if ZP symbol extension is used in practice as in the WiMedia solution.

The generated symbol vector applied to each sub-band can be restated as

$$S = F^H D \begin{bmatrix} C_1 & & & & \\ & \ddots & & & \\ & & C_b & & \\ & & & \ddots & \\ & & & & C_B \end{bmatrix} \begin{bmatrix} X_1 \\ \vdots \\ X_b \\ \vdots \\ X_B \end{bmatrix}, \quad (2)$$

where B is the number of blocks in the sub-band with $B \times L = N$, C_b the precoding matrix containing the K precoding sequences of block b , and X_b the K -dimensional vector containing the symbols to be transmitted within block b . In addition, a permutation matrix, denoted D , is used to interleave the chips resulting from the precoding process in the frequency domain.

B. MAC Layer

The MAC layer model is illustrated in Fig. 3. The two main tasks in this layer are classification and scheduling.

1) *QoS and service classes*: The MAC layer is responsible for QoS support for the multimedia applications. Hence, because of the various types of multimedia or real-time applications that can be used in UWB systems and that have strict QoS requirements (video recording, A/V conferencing, interactive gaming, etc), we define a two traffic classes model that differentiates between two traffic types: QoS (i.e. real-time traffic) and BE (i.e. non real-time or data traffic). The main goal is to guarantee a certain amount of resource for QoS traffics and to share the remaining amount of resource among BE traffics, in order to satisfy the multimedia applications constraints such as the error rate, the throughput, the delay, etc.

2) *Scheduler*: Scheduling is a main task in our model. Therefore, we define a scheduler that shall be able to classify all the users into the traffic classes (QoS or BE) and to assign a priority level for each traffic based on the traffic requirements and constraints (i.e. type of application, delay).

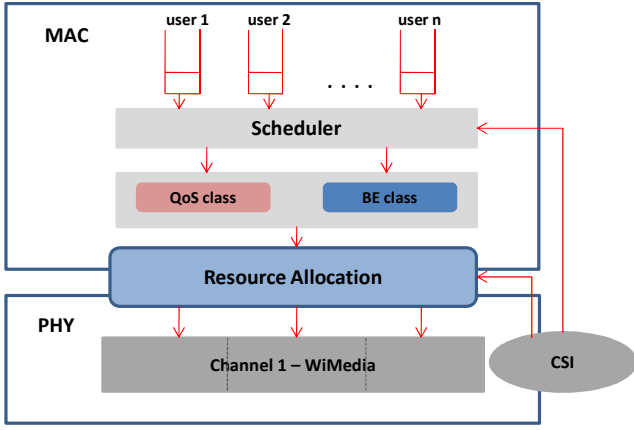


Fig. 3. Cross-layer model

After assigning this priority level, the scheduler combines it with the channel state information (CSI) provided by the physical layer, in order to make the allocation decision for each user as explained in the next section.

III. PROPOSED SCHEME

In a multi-user context taking into account the QoS issue, the aim of the proposed scheme is to improve the performance of the users having higher priority than other users, which in turn shall improve the total system capacity.

The total throughput in bit per symbol of a LP-OFDM user using a zero-forcing (ZF) detection is given by [11]

$$R_u = \sum_{b=1}^B \sum_{c=1}^{C_b} \log_2 \left(1 + \frac{1}{\Gamma} \frac{L^2}{\sum_{i=1}^L (1/|h_{i,b}|^2)} \frac{P_{c,b}}{N_0} \right), \quad (3)$$

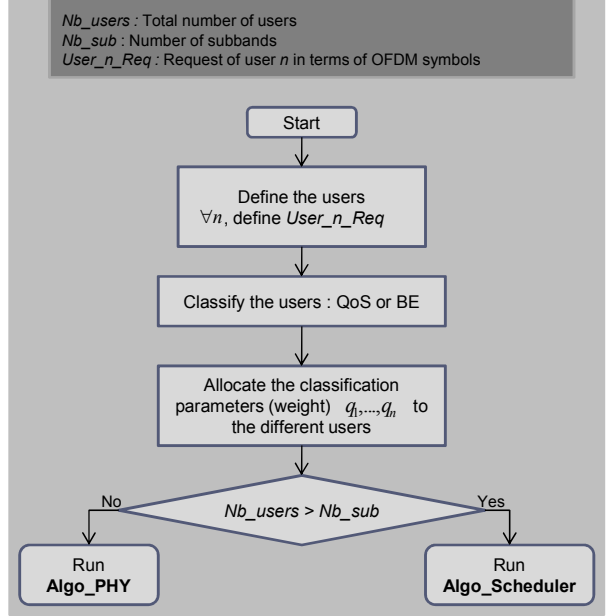
where Γ is the SNR gap of the quadrature amplitude modulation (QAM), B the number of blocks, C_b the number of used codes in block b , L the spreading code length, $h_{i,b}$ the frequency-domain response of subcarrier i in block b and $P_{c,b}$ the power allocated to code c within block b . In UWB case, this power density respects the following condition:

$$\sum_{c=1}^{C_b} P_{c,b} \leq P \quad \text{and} \quad P_{c,b} \geq 0, \forall b, \quad (4)$$

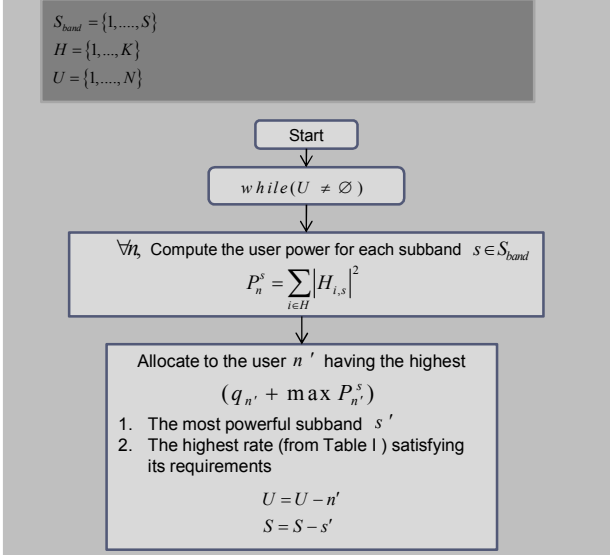
with P related to the PSD limit defined by the regulation authorities.

In order to optimize the resource allocation of the whole system, the sum of all user throughputs must be maximised. In other terms, we have to maximise each single user throughput while respecting its QoS requirements. Therefore, the problem of sharing the spectrum becomes critical, particularly when the number of users exceeds the number of the sub-bands on one channel. To solve this problem, we propose a cross-layer algorithm that allocates for each user the sub-band that reflects its requirements provided by the QoS (MAC) and the appropriate throughput provided by the CSI (PHY).

Algo_MAC



Algo_PHY



Algo_Scheduler

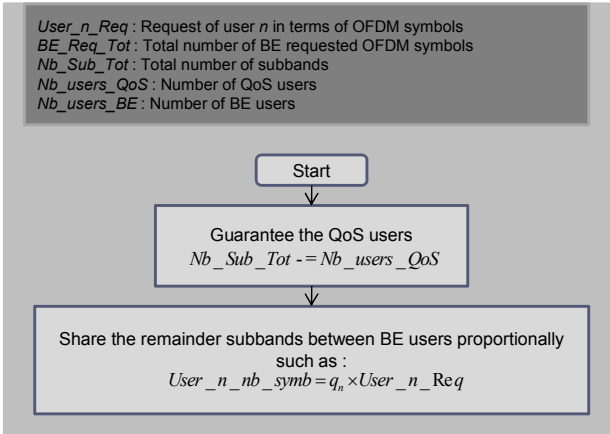


Fig. 4. Cross-layer algorithm

The algorithm is presented in Fig. 4. As illustrated in the figure, there are two main processes, each running at a level (one at MAC level and one at PHY level).

At the MAC level (Algo_MAC), the users are defined and characterized by their types and requirements that are translated into two effective parameters: the classification type (QoS or BE) and the number of OFDM symbols needed (or requested). After the classification, a weight q is attributed for each user (or application). More the user is high-classified, more his weight q is high. Then, it is checked if the number of users exceeds the number of available sub-bands; if it is the case, a scheduler (Algo_Scheduler) defines a strategy to allocate all the users in the available spectrum in an efficient way that respects the classification that differentiates between the available users, otherwise we move to the physical layer (Algo_PHY) in order to allocate to the classified users the available sub-bands. To do so, a priority level is assigned to each user in order to respect the main concept of differentiating the users. Having two essential parameters, the classification coefficient vector (provided by the MAC layer through the weight attribution) and the channel matrix (through the CSI knowledge) of all the users, a priority level PL, which is the combination of these two parameters, is assigned to each user ($PL = \text{weight} + \text{CSI}$). The user that has the higher priority level is allowed to choose the most powerful sub-band. The processes continue as long as there are users that are not assigned a sub-band.

IV. 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 [12]. This model is a modified version of Saleh-Valenzuela model for indoor channels [13], fitting the properties of UWB channels.

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.

B. Simulation Results

In this section, we present the simulation results for the proposed cross-layer allocation scheme and we compare the performance of the new scheme with the performance of WiMedia and LP-OFDM solutions using TFC. Therefore, we use the proposed LP-OFDM data rates (see Table I), which are close to the ones proposed by the WiMedia solution. The results are performed on the first three WiMedia sub-bands (3.1-4.7 GHz) for CM1 channel model.

In Fig. 5, we show through an example the strategy of cohabitating four users in one channel. The highest priority level user (QoS-PL1) is allocated the most powerful sub-band (sub-band 2), the QoS-PL2 is allocated sub-band 1 and the BE

TABLE I
LP-OFDM SYSTEM DATA RATES

Data rate (Mbit/s)	Modulation	Coding Rate	Load (C)	Coded bits Per symbol
51.2	QPSK	1/3	4	48
76.7	QPSK	1/3	6	72
115.1	QPSK	1/3	9	108
153.6	QPSK	1/3	12	144
192	QPSK	1/2	10	120
307	QPSK	1/2	16	192
409	QPSK	2/3	16	192
460	QPSK	3/4	16	192

users (BE-PL3) have to share sub-band 3 in a proportion depending on their priority level (in this example they have the same priority level). In this case, the BE users are forced to use half of the allocated rate and they will have a delay that is two times greater than the QoS users delay. This degradation in performance of BE users is acceptable, because of the tolerance of non-real time applications to the delay and the jitter.

In Fig. 6, the case of three users transmitting simultaneously in the first channel is shown. The three users have different data rates in order to show the advantage of QoS users on BE users in terms of error rate. The QoS user is allocated the highest rate from Table I (460 Mbit/s) and the BE users are allocated the second data rate (409 Mbit/s). As illustrated in the figure, the QoS user outperforms the BE users although it is transmitting at a higher data rate.

In Fig. 7, we compare the performance of the three users scheme having a same data rate of 307 Mbit/s with the performance of a single user adopted by WiMedia (at 320 Mbit/s) and LP-OFDM (at 307 Mbit/s) solutions. Note that for the single user solutions, TFC based is exploited for the comparison because it offers better performance. For $BER = 10^{-4}$, the cross-layer scheme offers a 2 dB gain for the real-time user (QoS-PL1) compared to the LP-OFDM solution, and a 2.5 dB gain compared to the WiMedia solution. For other users, the performance is close to that of the WiMedia and LP-OFDM solutions.

In Fig. 8, we present the performance of the four users scheme transmitting simultaneously in the first channel at the same data rate of 307 Mbit/s; two QoS users with two different priority levels and two BE users with the same priority level. In the same channel, the best sub-bands are guaranteed for the two QoS users respectively and the last sub-band is shared between the two BE users (as illustrated in Fig. 5). Hence, note that the rate of the BE users is divided by a factor of two, and actually equals to $307/2 = 153.5$ Mbit/s. As illustrated in the figure, the QoS constraint is respected and the QoS users outperforms the BE users.

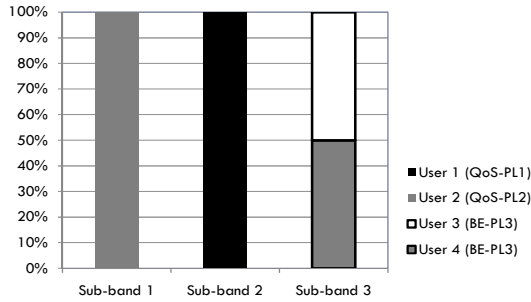


Fig. 5. Sub-band allocation for four users

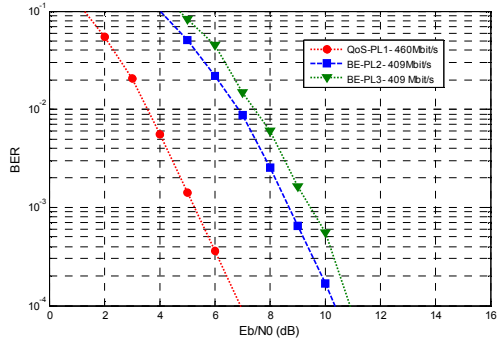


Fig. 6. Performance of three users transmitting simultaneously with different data rates

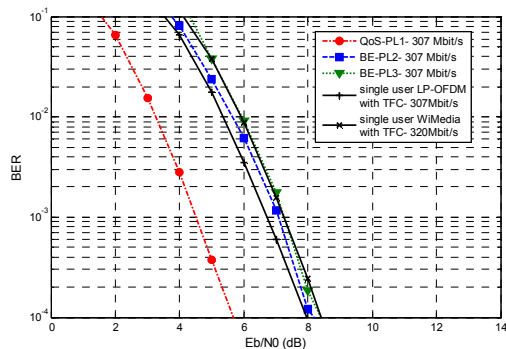


Fig. 7. Performance of the cross-layer scheme compared to LP-OFDM and WiMedia solutions using TFC

V. CONCLUSION

In this paper, we proposed a new cross-layer design for UWB systems. This design combines the physical layer information (CSI) and the MAC layer parameters (priority level and scheduling decision). This combination solves the problem of the cohabitation of more than three users in one channel defined in the WiMedia solution and it manages the users requirements and constraints, so that QoS users have advantage on BE users in term of error rate and quantity of resources. We showed that the proposed scheme improves the system performance without increasing its complexity, and it outperforms the WiMedia and LP-OFDM solutions for multimedia users.

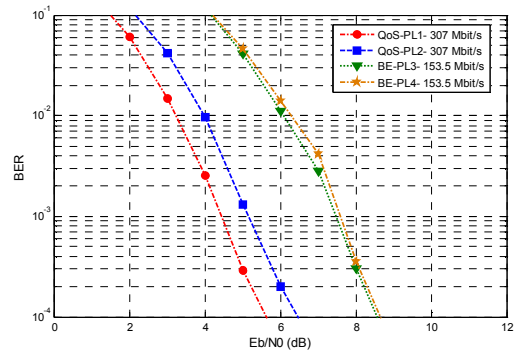


Fig. 8. Performance in a four users configuration

ACKNOWLEDGMENT

The research leading to these results has received funding from the European Community's Seventh Framework Programme FP7/2007-2013 under grant agreement n° 213311 also referred as OMEGA.

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