

# Cross-layer enhanced time scheduling for multi-band OFDM UWB networks

Mehmet Keskinöz · Ozgur Gurbuz ·  
Engin Masazade

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**Abstract** Multi-band Orthogonal Frequency Division multiplexing based Ultra Wide-band (MB-OFDM UWB) technology is one of the strong alternatives for high data rate wireless personal area networks (WPANs) with low power consumption. The capacity of such systems is degraded by multi-path fading, shadowing, multi-user interference and noise. To improve system capacity under these adverse effects, in this paper, we devise cross-layer time scheduling methods, Proportional Time Scheduling with Modiano Algorithm (*PTS-MA*) and Proportional Time Scheduling with Channel State Information (*PTS-CSI*), in which scheduling and link adaptation are performed using instantaneous bit error probability (IBEP) estimates obtained through Modiano's algorithm and our novel estimation technique, respectively. We evaluate the performance of the PTS schemes by using numerical experiments. Simulation results suggest *PTS-CSI* scheduler as the most promising candidate for practical MB-OFDM UWB WPANs with high capacity and fair throughput distribution.

**Keywords** Opportunistic scheduling · Link adaptation · Multi-band OFDM · Ultra-wide band · Instantaneous bit error estimation

## 1 Introduction

Ultra-wide band (UWB) systems have recently gained a lot of interest because of their abilities to provide high data rate transmission for wireless personal area networks

(WPANs) [1]. As specified by FCC, UWB systems are to operate at 3.1–10.6 GHz unlicensed band, using at least 528 MHz bandwidth with low power consumption and cost [2]. The growing demand for home networking has evolved from the development of entertainment technologies and applications such as video-on-demand, High Definition Television (HDTV) [3] and powerful personal computing devices, etc. The high bandwidth requirements of such applications cannot be satisfied by available wireless LAN technologies such as 802.11b, a, g. UWB WPANs readily promise to serve these demands by providing data rates up to 480 Mbps over short distances, removing the wires between the devices. Through wireless mesh networks, the range of high data rate WPANs can be extended, by using UWB for connecting several WPANs in the home [4–6].

Today's UWB proposals focus mostly on two techniques: direct sequence-UWB (DS-UWB) [7] and Multiband-OFDM-UWB [8, 9]. DS-UWB extends the impulse radio approach by applying direct sequence spread spectrum techniques to base-band pulses and spanning the entire UWB band. Contrary to that, Multiband-OFDM (MB-OFDM UWB) divides the UWB spectrum into equally spaced sub-bands and generates the UWB symbols with conventional OFDM techniques. Due to the virtues of OFDM (e.g., simple equalization, multipath, and interference resilience), in this work, we concentrate on the MB-OFDM approach. Specifically, we consider the MB-OFDM UWB proposal of Texas Instruments [8, 10].

MB-OFDM UWB links are subject to severe impairments such as multi-path fading, shadowing, multi-user interference, etc., which degrade the channel quality and make it highly variable in time and space. This causes lots of packet losses and retransmissions, so the offered high data rates of MB-OFDM links cannot be utilized. One way to compensate for this loss and to boost the capacity of

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M. Keskinöz (✉) · O. Gurbuz · E. Masazade  
Faculty of Engineering & Natural Sciences, Sabanci University,  
Istanbul 34956, Turkey  
e-mail: keskinoz@sabanciuniv.edu

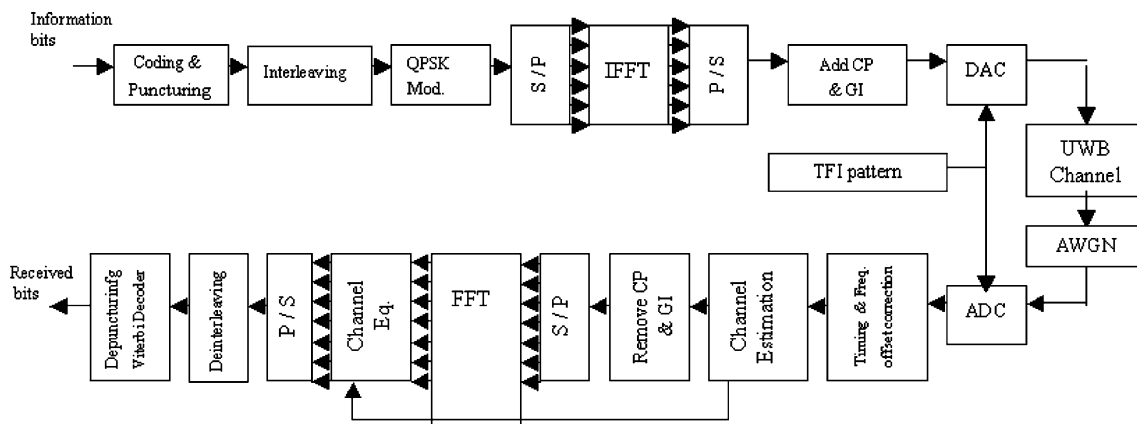
MB-OFDM networks is by scheduling users' transmissions and enhancing the throughput of MB-OFDM links. Opportunistic scheduling algorithms [11–13] have been shown to maximize wireless system capacity by making use of the channel variations, i.e., riding the peaks. In these approaches, a constant size packet is transmitted by a scheduled user in a single scheduling instant. However, in the access layer of MB-OFDM UWB WPANs, defined by IEEE 802.15.3, the transmission durations can vary between users, transmission durations of multiple users (or links) are to be determined over an access period and scheduling is left out of the standard [10]. For this purpose, in this paper, first we propose Proportional Time Scheduling (*PTS*) as a scheduling scheme for MB-OFDM WPANs, where the multiple channel time allocations of multiple links are determined opportunistically, so that overall network efficiency and throughput is maximized. The second way to boost the capacity of the MB-OFDM network is to improve the efficiency of MB-OFDM links under channel degradations by link adaptation, which is adjusting the transmitted frame sizes optimally based on the instantaneous bit error probability (IBEP) when an ARQ method is employed [14]. The third approach to increase the network throughput further is to combine the previously mentioned two approaches, i.e., to perform *PTS* and link adaptation together, based on the cross-layer information in terms of IBEP estimates. With this motivation, we develop two cross-layer enhanced *PTS* schemes: In Proportional Time Scheduling with Modiano Algorithm (*PTS-MA*), IBEP estimates are first obtained via Modiano's estimation Algorithm (*MA*) [14] and these IBEP estimates are then used to calculate the instantaneous link efficiencies, which determine the channel time allocations of links in *PTS*. We show that *PTS-MA* improves the network throughput notably, as compared to the standard equal time sharing method, which serves links in a round robin fashion with fixed frame sizes (i.e., with no link adaptation).

However, *PTS-MA* requires a number of frame transmissions prior to the Modiano's estimation process, which makes the tracking of the channel difficult and deteriorates the reliability of IBEP estimation, especially when the number of active links is increased. To remedy this problem, a novel and more accurate IBEP estimation technique for time-varying MB-OFDM UWB fading channel is developed and incorporated into the *PTS* algorithm. This second scheduler is named as Proportional Time Scheduling with Channel State Information (*PTS-CSI*), where the instantaneous channel state formation (CSI) is used to estimate the IBEP values. Through the numerical experiments, we also show that *PTS-CSI* outperforms *PTS-MA* significantly (by up to 60%), and maintains high network throughput consistently, irrespective of the number of active links.

The rest of the paper is organized as follows. Section 2 reviews the system model, WPAN physical (PHY) and medium access control (MAC) layers. Section 3 briefly summarizes related work on scheduling and then presents our *PTS* approach and link adaptation. Likewise, in Sect. 4, the existing IBEP estimation method, *MA* and our proposed IBEP estimation technique are introduced. Following that, in Sect. 5, the proposed cross-layer enhanced *PTS* methods, *PTS-MA*, and *PTS-CSI*, are presented and performance results are given in Sect. 6. Finally, our conclusions appear in Sect. 7.

### 1.1 WPAN model

According to the MB-OFDM UWB proposal of Texas Instruments (TI) [8], the available UWB spectrum is divided into 14 equally-spaced 528 MHz sub-bands. However, the current form of the proposal utilizes the first three sub-bands for implementation simplicity and the rest of sub-bands are reserved for future use. Figure 1 depicts the transmitter-receiver chain in MB-OFDM UWB system,



**Fig. 1** MB-OFDM based UWB system model

where the information bits are first convolutionally encoded and punctured. The encoded/punctured data stream is then passed through a two-stage interleaver. The first stage interleaver performs interleaving across the MB-OFDM sub-bands, and the second stage performs interleaving across the OFDM sub-carriers. Following that, the interleaved bit stream is mapped to QPSK symbols from which the time domain sequence is obtained by IFFT just after serial-to-parallel conversion. The analog information-bearing signal is obtained by performing a parallel-to serial conversion at the output of the IFFT block followed by a raised-cosine filter. Consecutive analog OFDM symbols are up-converted to the associated sub-bands according to a predefined time-frequency interleaving pattern. The signal at the output of the transmitter passes through the noisy UWB channel for which IEEE’s UWB fading model together with free space path loss channel model [15, 16] is considered. The MB-OFDM UWB receiver basically undoes the operations performed in the transmitter and uses soft Viterbi Algorithm (VA) to decode the convolutional code.

We consider a basic WPAN piconet with a number of devices as illustrated in Fig. 2, where one of the devices assumes the role of the piconet coordinator (PNC). The PNC provides basic timing, power control, and medium access to all devices. This piconet employs IEEE 802.15.3 MAC [10] with physical layer defined by MB-OFDM UWB proposal of Texas Instruments (TI) in [8]. The PHY layer parameters for the highest data rate 480 Mbits/s are summarized in Table 1.

The 802.15.3 Medium Access Control (MAC) employs a centralized, connection-oriented approach that makes use of both random and TDMA type access. The PNC utilizes the superframe structure shown in Fig. 3 for controlling channel access. During the beacon period, the devices inside the piconet synchronize with the PNC, the devices are informed about the duration of the current superframe,

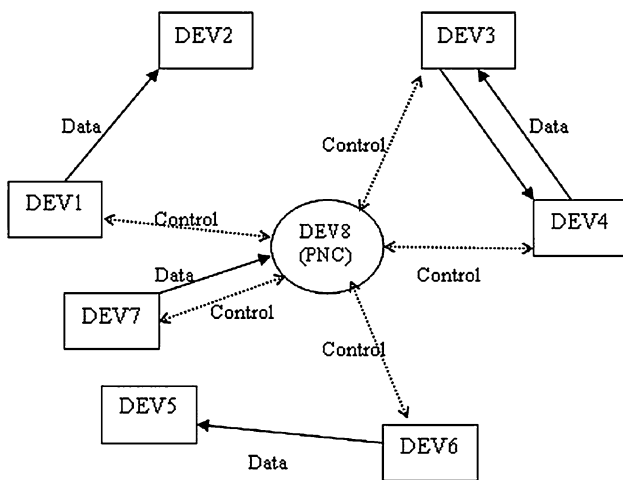


Fig. 2 IEEE 802.15.3 piconet

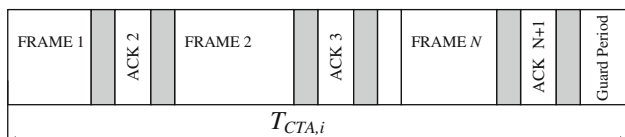
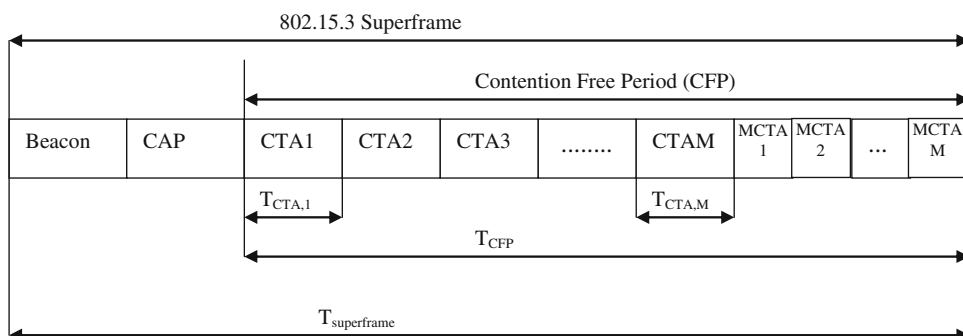
Table 1 MB-OFDM physical layer parameters

Data rate (R)	480 Mbps
Modulation	QPSK
Coding rate	$\frac{3}{4}$
Generator polynomials	$g_0 = [133]_8, g_1 = [145]_8, g_2 = [175]_8$ .
Constraint length (K)	7
$N_{CBPS}$ : Coded bits per OFDM symbol	200
$N_{DBPS}$ : Data bits per OFDM symbol	150
IFFT/FFT size (Total number of sub-carriers)	128
Number of data sub-carriers $N_{SC}$	100
Number of defined sub-carriers	12
Number of undefined sub-carriers	10
Number of zero sub-carriers	6
Symbol bandwidth (W)	528 MHz
Subcarrier spacing between sub-carriers	4.125 MHz
$T_{IFFT/FFT}$ : IFFT/FFT duration	242.42 ns
$T_{CP}$ : Cyclic prefix duration	60.61 ns
$T_{GI}$ : Guard interval duration	9.47 ns
$T_{SYM}$ : Symbol duration	312.5 ns
RC Filter roll-off factor	0.5
Sub-band 1 center frequency ( $f_1$ )	3432 MHz
Sub-band 2 center frequency ( $f_2$ )	3960 MHz
Sub-band 3 center frequency ( $f_3$ )	4488 MHz
Time & Freq. Int. Pattern	$f_1f_2f_3f_1f_2f_3$

beginning and end of the contention access period (CAP), start of the contention free period (CFP), and the timing of individual channel time allocations. When a device wants to initiate a link with another device, it sends a channel request frame to the PNC during CAP that employs Carrier Sense Medium Access with Collision Avoidance (CSMA/CA) [17]. CFP is composed of channel time allocations (CTAs) and management channel time allocations (MCTA), which are isolated time-windows dedicated for carrying data or management frames for a link. The current IEEE 802.15.3 standard does not involve a scheduling scheme for managing the time allocations of channel requests within CFP [10].

Once a connection is set up and declared by the PNC, the data communication takes place between devices in a peer-to-peer manner during the CTA as shown in Fig. 4. The delivery of a frame through a connection between devices can be verified using one of the three acknowledgement (ACK) policies: No-ACK, immediate ACK (Imm-ACK) and delayed ACK policy (Dly-ACK). Imm-ACK policy provides an ACK for each individual transmitted frame, which is equivalent to the Stop-and-Wait ARQ protocol. In the Dly-ACK, the transmitter sends multiple frames to the receiver; the acknowledgement for

**Fig. 3** IEEE 802.15.3 superframe structure



**Fig. 4** Channel Time Allocation (CTA) of the *i*th link in the contention free period

those frames is grouped and sent back to the transmitter when requested. Since Imm-ACK policy is practical for MB-OFDM channels that have low propagation delay, in this paper, the Imm-ACK policy is selected for the link layer of the system.

In the next section, we discuss how the capacity of a MB-OFDM UWB piconet can be improved by optimizing the frame size for ARQ link efficiency and by designing proportional time scheduling scheme for managing CTAs.

**2 Link adaptation and proportional time scheduling for MB-OFDM UWB WPANs**

As pointed out earlier, the current form of the IEEE 802.15.3 WPAN MAC does not include a scheme to manage the time allocations of channel requests. The existing scheduling schemes proposed for UWB WPANs, mostly concentrate on service differentiation for Quality of Service (QoS) [18, 19]. These schemes employ time allocations based only on QoS without taking the physical layer information into account and assuming all links are similar. Unfortunately, these schemes are vulnerable to variations in channel quality resulting in frame failures and low throughput, since all links are typically subject to different fading conditions. On the other hand, the variations in the wireless channel can be exploited by the so-called opportunistic scheduling methods [11–13], where the basic idea is to schedule the resources to links/users with better channel conditions. In [11], the user with the highest channel capacity is selected and, despite maximizing capacity, such greedy algorithms can cause unacceptable delays and unfairness. The proportional fair

approach [12] mitigates this problem by selecting users according to their relative channel conditions with respect to their own history, resulting in better fairness but lower throughput. In [13], the opportunistic approach is extended to multi channel/carrier systems and the proposed opportunistic OFDM scheduler decides which time-slot, as well as which sub-carrier should be allocated to each user. This scheme is not only complex and exhaustive, but also allocation of sub-carriers would require changes in the physical layer of MB-OFDM system. Furthermore, in all of these approaches, scheduled transmissions assume assigning a single packet transmission of constant size to a single user, and selection decision is performed for each scheduling instant, which is a time slot. The MAC layer of MB-OFDM WPANs, specified by IEEE 802.15.3 involves contention free periods, over which the scheduled users are to be allocated their channel time allocations, as revised in the previous section.

In this paper, we propose a simple opportunistic time scheduling approach designed for IEEE 802.15a MAC of WPANs, where variable time allocations are reserved to UWB MBOFDM links to maximize the overall network throughput based on the link efficiencies. This scheme is named as *PTS*, where the duration of time allocation (CTAs) of each communicating link *i*,  $T_{CTA,i}$  is assigned proportionally with respect to the instantaneous efficiency values as follows:

$$T_{CTA,i} = \frac{\eta_i}{\sum_{i=1}^M \eta_i} T_{CFP} \quad i = 1, 2, \dots, M \tag{1}$$

*M* is the number of channel requesting links and  $\eta_i$  is the efficiency of *i*th link which can be measured over large number of frame transmissions. Considering various channel realizations of the time-varying MB-OFDM channel, instantaneous efficiency of *i*th link is measured as

$$\eta_i = \frac{\frac{(\# \text{ of bits delivered in all channel realizations})}{(\# \text{ of channel realizations}) \times T_c}}{R} \tag{2}$$

where  $T_c$  is the coherence time of the channel and *R* is the data rate in the channel.

In *PTS*, the time allocations in an upcoming CFP are determined based on efficiency measurements in the

current CFP. These measurements can be performed at the sender or the receiver of the link. The node that performs the measurement delivers this information to the PNC via management frames of 802.15.3 during management time allocations (MCTA). *PTS* is also an opportunistic approach since more time is allocated to transmissions with high link efficiency.

Other than opportunistic multi-user scheduling scheme, the second way to improve the throughput of a MB-OFDM network is to optimize the frame size for individual links by using the bit error probability (IBEP) estimates instantaneously. For this purpose, we next calculate the efficiency of a MB-OFDM link employing Imm-ACK policy as a function of IBEP.

The transmission efficiency [17],  $\eta_0$ , of an error-free MB-OFDM UWB link using Imm-ACK policy can be calculated as

$$\eta_0 = \frac{1}{R} \frac{8 \times N_{\text{FRAME}}}{T_{\text{SYM}} \times \left( N_{\text{PR}} + N_{\text{MAC}} + 3 \times \text{ceil} \left( \frac{\text{round} \left( \frac{N_{f,\text{bits}}}{r} \right)}{3 \times N_{\text{CBPS}}} \right) \right)} \tag{3}$$

where  $R$  is the data rate in bps,  $N_{\text{FRAME}}$  is the frame size in terms of bytes,  $T_{\text{SYM}}$  is the OFDM symbol duration,  $r$  is the coding rate,  $N_{\text{MAC}}$  is the number of the OFDM symbols in the MAC preamble,  $N_{\text{CBPS}}$  is the number of coded bits per OFDM symbol, and  $N_{\text{PR}}$  is the number of the OFDM symbols carried inside a Physical Layer Convergence Procedure (PLCP) preamble.  $N_{f,\text{bits}}$  is the number of information bits per frame calculated as  $N_{f,\text{bits}} = 8 \times N_{\text{FRAME}} + N_{\text{FCS}} + K - 1$ , where  $N_{\text{FCS}}$  is the number of redundant bits for the checksum and  $K$  is the constraint length of convolutional code. Note that because of the usage of three bands in the TI proposal, we have a factor of three to calculate the number of OFDM symbols per frame in Eq. 1. Further details can be found in [8, 10].

When the packets are transmitted over an erroneous channel with IBEP of  $\rho$ , the expected time to deliver a frame successfully,  $E[t_{\text{total}}]$ , can be directly determined from [17],

$$E[t_{\text{total}}] = \frac{t_0}{(1 - P_f)}, \tag{4}$$

where  $t_0$  is the time needed to send a frame assuming error-free transmission and  $P_f$  is the frame error probability expressed in terms of IBEP as,<sup>1</sup>

$$P_f = 1 - (1 - \rho)^{8 \times N_{\text{FRAME}} + N_{\text{FCS}}}. \tag{5}$$

Finally, the efficiency,  $\eta$ , of the MB-OFDM link using Imm-ACK policy can be determined as

$$\eta = \frac{8 \times N_{\text{FRAME}}}{E[t_{\text{total}}] \times R} = \eta_0 \times (1 - \rho)^{(8 \times N_{\text{FRAME}} + N_{\text{FCS}})} \tag{6}$$

The optimum frame size  $N_{\text{FRAME}}^*$  that maximizes  $\eta$  can be found from

$$N_{\text{FRAME}}^* = \arg \max_{N_{\text{FRAME}}} \eta \quad N_{\text{FRAME}} = 0, \dots, 4095\text{B}, \tag{7}$$

where the limits are the minimum and maximum frame payload sizes from [8].

Therefore, by knowing or predicting the IBEP, one can calculate the ARQ link efficiency using Eq. 6 and thereby the frame size can be optimized according to Eq. 7. This information can also be utilized in *PTS*. Hence, the estimation of the IBEP with knowledge of the CSI has utmost importance for the design of *PTS* scheduling algorithms, so that the throughput of the individual links as well as the entire network will be improved.

### 3 IBEP estimation for MB-OFDM UWB WPANs

The estimated IBEP can be utilized in link adaptation via frame size adaptation and design of scheduling algorithms which determine the time allocations (CTAs), both of which are expected to improve the network throughput. Hence, in the following sub-sections, we first briefly describe the related work on IBEP estimation and then we present our proposed approach.

### 4 Existing work

The performance of time-varying MB-OFDM UWB channels can be quantified by the average bit error probability (ABEP) based on the knowledge of the channel statistics. Recent work [20] derives ABEP bounds of convolutionally coded MB-OFDM systems using the channel statistics. Although ABEP shows the channel performance on the average, it does not provide any information about performance of the system instantaneously. Moreover for a given average bit energy per noise spectral density, i.e.,  $E_b/N_0$ , the actual channel IBEP can deviate from the ABEP. Therefore, IBEP associated with a particular realization of the MB-OFDM channel can be a useful measure of the instantaneous channel performance. Hence, knowing the IBEP rather than the ABEP, for example, allows us to optimize the frame size dynamically and thereby boost the capacity and maximize the throughput of a wireless link.

<sup>1</sup> Here, we assume that Imm-Ack packets are transmitted without errors, since such small control packets can be well protected by strong error correction.

A prominent IBEP estimation technique from the literature is proposed by Modiano [14]. This algorithm monitors a number of retransmitted frames,  $C$ , out of the number of previously transmitted frames,  $D$ . Given that the retransmissions occur only for the frames in error and the channel introduces independent bit errors within the channel coherence time, the maximum likelihood (ML) estimate of the IBEP can be obtained as

$$\hat{\rho} = \arg \max_{\rho} P[C|\rho] = \arg \max_{\rho} \left\{ \binom{D}{C} P_f^C (1 - P_f)^{(D-C)} \right\} \quad (8)$$

This maximization can be done by taking the log derivative of the above equation and setting it equal to zero and solving for  $\rho$  by employing Eq. 5. Hence, the ML estimate,  $\hat{\rho}$ , can be obtained as

$$\hat{\rho} = 1 - \left( 1 - \frac{C}{D} \right)^{\frac{1}{(8 \times N_{\text{FRAME}} + N_{\text{FCS}})}} \quad (9)$$

However, the ML estimate of  $\rho$  tends to overestimate or underestimate the IBEP when there are too many or few bit errors, respectively. For example, when no errors occur in the  $D$  transmissions,  $\hat{\rho}$  can be determined as zero implying an infinite frame size and when the IBEP of the link is too high, the optimum frame size scales down to zero. To avoid such biases, the frame sizes are restricted to the range of payload sizes as defined in [10]. The frame sizes are then selected according to,

$$N_{\text{FRAME}} = \begin{cases} 4095 \text{ bytes} & C = 0 \\ N_{\text{FRAME}}^* & 0 < \frac{C}{D} < 1 \\ 1 \text{ byte} & C = D \end{cases} \quad (10)$$

When the channel is clear, the transmitter selects the maximum frame size to achieve the best channel utilization. When the channel introduces some frame errors, transmitter uses Eq. 9 to estimate the channel IBEP and optimizes the frame size accordingly. When the link is in deep fade, all of the previously transmitted frames are in error and the transmitter selects the minimum frame size, one byte. Throughout this manuscript, it is also assumed that the characteristic of the MB-OFDM link is invariant during the channel's coherence time. Hence, when a link just enters new fading conditions, Modiano's algorithm selects the optimal frame size based on the ML estimate of the IBEP. As long as the channel's coherence time is large enough,  $D$  can be observed and Modiano's method converges to the optimal frame size since the ML estimator variance becomes small enough to ensure the convergence. Since Modiano's algorithm tracks the channel using the previously transmitted  $D$  frames, we have tested this algorithm for different values of  $D$  via simulations. We have observed that as  $D$  is increased the

accuracy of the IBEP estimates are improved at the expense of increased convergence time, which makes it difficult to track the channel variations; whereas for low values of  $D$ , channel tracking is fast but estimation errors become severe. Therefore, as in [14] we obtain that values of  $D$  around 50 provides a good compromise between accuracy and tracking capability. Hence, we use  $D = 50$  with  $MA$  in the simulation results presented afterwards.

The IBEP estimate found in Eq. 9 is valid when channel introduces independent bit-errors. Even though channel introduces bursty bit errors due to fading, the assumption of independent bit errors is justified through the use of two-stage interleaving operation as mentioned in Sect. 2.

The advantage of  $MA$  is that it is a generic algorithm in the sense that it can be applied to any wireless system irrespective of the PHY layer structure. However, the main disadvantage  $MA$  is that it requires  $D$  frame transmissions to make an accurate IBEP estimation, so as the channel coherence time decreases; it becomes hard to track the variations of the channel. To alleviate this problem, in the next subsection, we propose a new method to estimate the IBEP by considering the PHY layer properties of the MB-OFDM channel.

## 5 Proposed IBEP estimation method

In this part, we present a new method to estimate the IBEP of MB-OFDM UWB system based on the CSI, which remedies the previously mentioned disadvantages of  $MA$ .

For a single carrier system, data is correctly received if the channel's instantaneous SNR is greater than some minimum required value. Otherwise, receiver declares outage that is, the received bits will be decoded incorrectly [21]. Therefore, we define the minimum required SNR to decode bits correctly as the outage threshold (OT). Hence, the average information rate correctly received over many transmission bursts over a single carrier system with instantaneous SNR of  $|h|^2/\sigma^2$  and bandwidth of  $B$  Hz can be written as [21]

$$C_{\text{out}} = (1 - P_{\text{out}}) B \log(1 + \gamma) \quad (11)$$

where  $\gamma$  is the outage threshold and  $P_{\text{out}}$  is the outage probability that equals to  $P\left(\frac{|h|^2}{\sigma^2} < \gamma\right)$ .

$C_{\text{out}}$  shows the reliable information rate on the average, rather than the instantaneous reliable information rate for a given CSI. Hence, it can serve as a useful measure for the average bit error probability (ABEP) rather than instantaneous bit error probability (IBEP). Therefore, we need to obtain a new capacity based measure that quantifies the instantaneous reliable information rate for a given CSI. For this purpose, we first define instantaneous reliable information rate for a single carrier system as

$$C_{\text{out}}(h) = \left(1 - I_\gamma\left(\frac{|h|^2}{\sigma^2}\right)\right) B \log_2\left(1 + \frac{|h|^2}{\sigma^2}\right) \quad (12)$$

where  $I_\gamma(\cdot)$  is an indicator function that is one if the carrier SNR is below the outage threshold,  $\gamma$ , or zero otherwise, which can be expressed mathematically as

$$I_\gamma\left(\frac{|h_i|^2}{\sigma^2}\right) = \begin{cases} 1 & \text{if } \frac{|h_i|^2}{\sigma^2} < \gamma \\ 0 & \text{otherwise} \end{cases} \quad (13)$$

For a multi carrier system with  $N$  sub-carriers, the instantaneous reliable sum-rate can be written as

$$C_{\text{out}}^{\text{sum}}(\mathbf{H}) = \sum_{i=1}^N \left(1 - I_\gamma\left(\frac{|h_i|^2}{\sigma^2}\right)\right) \frac{B}{N} \log_2\left(1 + \frac{|h_i|^2}{\sigma^2}\right) \quad (14)$$

where  $\mathbf{H} = [h_1 \ h_2 \ \dots \ h_N]^T$  is the vector of instantaneous channel gains of all sub-carriers,  $B/N$  is the bandwidth allocation for each sub-carrier and  $|h_i|^2/\sigma^2$  denotes the signal to noise (SNR) ratio of the  $i$ th sub-carrier.

Note that,  $C_{\text{out}}^{\text{sum}}(\mathbf{H})$  is not the exact outage capacity of multi-carrier system, but the sum of instantaneous reliable information rates computed based on the individual reliable information rates of all subcarriers. The instantaneous reliable sum-rate in Eq. 14 can be rewritten as an inner product of two vectors  $\mathbf{x}$  and  $\mathbf{y}$  of length  $1 \times N$ , whose elements can be, respectively, expressed as,

$$x_i = \frac{1}{N} \left(1 - I_\gamma\left(\frac{|h_i|^2}{\sigma^2}\right)\right) \text{ and } y_i = B \log_2\left(1 + \frac{|h_i|^2}{\sigma^2}\right) \quad (15)$$

Since all vector elements are non-negative and using Cauchy-Schwartz inequality,

$$\langle \mathbf{x}, \mathbf{y} \rangle = \mathbf{x}^T \mathbf{y} \leq \|\mathbf{x}\|_2 \|\mathbf{y}\|_2 \quad (16)$$

and using also the fact that  $L_2$  norm of a vector is less than or equal to  $L_1$  norm, i.e., [22],  $C_{\text{out}}^{\text{sum}}(\mathbf{H})$  is bounded as,

$$\begin{aligned} & \sum_{i=1}^N \left(1 - I_\gamma\left(\frac{|h_i|^2}{\sigma^2}\right)\right) \frac{B}{N} \log_2\left(1 + \frac{|h_i|^2}{\sigma^2}\right) \\ & \leq \sum_{i=1}^N \left(\frac{1}{N} - \frac{1}{N} I_\gamma\left(\frac{|h_i|^2}{\sigma^2}\right)\right) \times \sum_{i=1}^N B \log_2\left(1 + \frac{|h_i|^2}{\sigma^2}\right) \end{aligned} \quad (17)$$

$$C_{\text{out}}^{\text{sum}}(\mathbf{H}) \leq c \left[1 - \frac{1}{N} \sum_{i=1}^N I_\gamma\left(\frac{|h_i|^2}{\sigma^2}\right)\right] \quad (18)$$

where  $c = \sum_{i=1}^N B \log_2\left(1 + \frac{|h_i|^2}{\sigma^2}\right)$  is a constant for a given channel realization. Therefore, the upper bound for  $C_{\text{out}}^{\text{sum}}(\mathbf{H})$  becomes a function of the instantaneous channel

realization,  $\mathbf{H}$ , and the outage threshold,  $\gamma$ . The upper bound for the  $C_{\text{out}}^{\text{sum}}(\mathbf{H})$  in Eq. 18 can be re-expressed as

$$C_{\text{out}}^{\text{sum}}(\mathbf{H}) \leq c[1 - F_\gamma(\mathbf{H})] \quad (19)$$

In the above equation,  $F_\gamma(\mathbf{H})$  is obtained as  $F_\gamma(\mathbf{H}) = \frac{1}{N} \sum_{i=1}^N I_\gamma\left(\frac{|h_i|^2}{\sigma^2}\right)$  and it determines the percentage of the sub-carriers whose signal-to-noise ratio is below the outage threshold  $\gamma$ , which we call instantaneous outage rate (IOR). Therefore, the instantaneous reliable sum-rate is upper-bounded by the percentage of sub-carriers whose signal-to-noise (SNR) ratio is bigger than a predefined outage threshold, i.e.,  $1 - F_\gamma(\mathbf{H})$ .

If the IOR of the channel realization is small, it is expected that this realization has a relatively high capacity or small number of bit errors. Therefore, we expect a minimum correlation between IBEP and the reciprocal of IOR for a given channel realization and outage threshold. Hence, the optimal value for the outage threshold  $\gamma^*$  can be found by minimizing the average correlation coefficient between the reciprocal of IOR and the IBEP as

$$\gamma^* = \arg \min_{\gamma} \delta(\gamma) \quad (20)$$

where the average correlation coefficient,  $\delta(\gamma)$  is calculated over the all possible channel realizations as

$$\delta(\gamma) = \frac{\text{COV}_{\mathbf{H}}[\text{IBEP}(\mathbf{H}), 1/F_\gamma(\mathbf{H})]}{\sqrt{\text{VAR}_{\mathbf{H}}[\text{IBEP}(\mathbf{H})] \times \text{VAR}_{\mathbf{H}}[1/F_\gamma(\mathbf{H})]}} \quad (21)$$

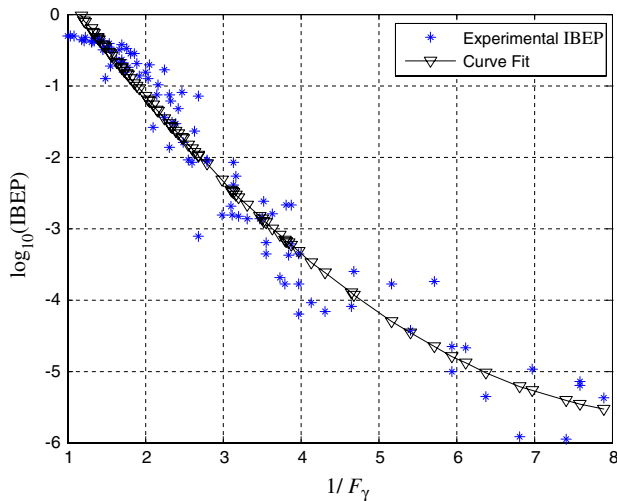
The notations  $\text{COV}_{\mathbf{H}}$  and  $\text{VAR}_{\mathbf{H}}$  are used to stress that the statistical averaging is performed over the random vector  $\mathbf{H}$  in the calculations of the covariance and variance, respectively.

In order to find the optimal outage threshold in Eq. 20, the average correlation coefficient is calculated over various independent UWB channel realizations through Monte Carlo simulations. For each channel realization, the distance between the transmitter and the receiver is kept fixed at 3 m. We take the same average noise power per information and the link budget parameter values as specified in [8].

For data rate of 480 Mbps, the optimal outage threshold is determined using Eqs. 20 and 21 as  $\gamma^* = 3$ . After determining the optimal outage thresholds, we next plot  $\log_{10}(\text{IBEP})$  as function of  $1/F_\gamma(\mathbf{H})$  using about 100 channel realizations in the Fig. 5. From this figure, one can deduce that a quadratic curve can essentially approximate the behavior of the  $\log_{10}(\text{IBEP})$  as a function of  $1/F_\gamma(\mathbf{H})$ . Therefore, a simple IBEP model can be developed as

$$\text{IBEP}(\mathbf{H}) = 10^{a(1/F_\gamma(\mathbf{H}))^2 + b(1/F_\gamma(\mathbf{H})) + c}, \quad (22)$$

where the model parameters  $a$ ,  $b$ , and  $c$  are obtained by minimizing the mean square error in quadratic-curve



**Fig. 5** IBEP as a function of  $1/F_\gamma(\mathbf{H})$  for various channel realizations and  $\gamma^* = 3$

**Table 2** Quadratic curve fitting parameters

$a$	0.0734
$b$	-1.462
$c$	1.643

fitting (Table 2). Using these values of the model parameters and the proposed model in Eq. 20, approximate IBEP values are quite accurate and consistent with the empirical IBEP values for various channel realizations as shown in Fig. 5.

## 6 Cross-layer enhanced proportional time scheduling

As previously pointed out, cross-layer information in terms of IBEP estimates can be used for opportunistic scheduling and to adapt MAC layer parameters optimally. The IBEP estimation can be performed at the receiver, and this knowledge can be delivered to the transmitter through ACK frames. With this motivation, in this section, we develop two cross-layer improved time scheduling schemes: Proportional Time Scheduling based on Modiano's Algorithm (*PTS-MA*) and Proportional Time Scheduling based on CSI (*PTS-CSI*), respectively.

In *PTS-MA* method, a number of ( $D$ ), frames are to be sent in advance, so that Modiano's Algorithm can be performed for IBEP estimation. For every transmitted set of  $D$  frames, the IBEP estimation is performed, the frame size adaptation is done accordingly and the maximum efficiency figures are sent to the PNC to allocate the time slot durations. Until the next IBEP update, for each CFP, *PTS* is applied according to instantaneously measured link efficiencies according to Eqs. 1 and 2. Note that, when there

are a large number of connections, the allocated time for each link is small and the number of transmitted frames per link may fall below  $D$ , which may deteriorate the reliability of Modiano's IBEP estimation.

In *PTS-CSI*, our proposed IBEP estimation method is employed and incorporated into *PTS*. In this scheme, IBEP estimation is performed using channel estimation preambles according to Eq. 22 for each frame within a channel time allocation. Based on these estimates, frame sizes are updated to maximize the link efficiency of each connection according to Eqs. 6 and 7. At the end of the CTA, the receiver computes the maximum link efficiency based on latest IBEP estimation and sends this information to the PNC. The PNC assigns the time allocations in an opportunistic manner as defined in Eq. 1.

For both methods, when a link is in a deep fade, the efficiency of that link can be close to zero, resulting in zero time allocation for that link in the next CFP. In order to provide fairness among users, some monitoring time should be allocated for those faded links, so that the PNC can track the new channel conditions and thereby update the subsequent time allocations accordingly. This monitoring time should be selected long enough to transmit one frame, introducing extra overhead for both scheduling schemes. This overhead can be costly and delay the estimation in *PTS-MA* since *MA* requires transmission of  $D$  frames. *PTS-CSI*, on the other hand, requires minor monitoring overhead since IBEP estimation and link adaptation are employed per frame. When a link fades, the frame size can be immediately updated to a small value and when that link recovers, the new channel condition will be tracked quickly using only a single frame. The monitoring period can have significant impact on the performance of the proposed cross layer enhanced scheduling schemes, as analyzed in the next section.

## 7 Performance results

In this section, the performance of our proposed scheduling schemes *PTS-MA* and *PTS-CSI* are evaluated for varying number of links. As two limiting cases, we also consider *PTS* schedulers with perfect link adaptation (*PTS-THEO*), and no link adaptation (*PTS-NLA*). In *PTS-THEO*, the ideal IBEP estimates are incorporated into *PTS*, while in *PTS-NLA*, a constant (maximum) frame size of 4095 bytes is used. In order to compare the *PTS* based methods, we have also considered a basic scheduling scheme, namely, *Equal Time Sharing Scheduling (ETS)* which reserves equal time for each link in a round-robin fashion. Likewise, *ETS-CSI* performs link adaptation using our proposed IBEP estimation method and *ETS-NLA* operates with a constant frame size of 4095 bytes.

In our experiments, we have simulated MB-OFDM UWB physical layer and IEEE 802.15.3 WPAN MAC layer described in Sect. 2. We consider a single piconet, where all devices are 3 m away from the PNC. The air interface parameters of all links are set according to Table 1. The average noise power per information bit and the link budget parameters are taken from the specification [8]. In modeling the wireless links, we have considered IEEE UWB channel model [15, 16] with multi-path fading, AWGN and path loss effects, and we have simulated 100 different realizations of this channel. The coherence time of time-varying MB-OFDM UWB channel is modeled as 10 ms [18], which is consistent with the mobility rates in WPANs.

We first obtain the total throughput of the MB-OFDM UWB piconet for different number of simultaneously operating links as shown in Fig. 6. When *ETS* scheme is employed with no link adaptation, the 480 Mbps MB-OFDM UWB channel is underutilized at 53% efficiency. *PTS* by itself (with no link adaptation) improves the throughput of *ETS* by up to 38%, as seen from *PTS-NLA* and *ETS-NLA* curves. However, as the number of active links is increased, the performance of *PTS-NLA* is considerably degraded, approaching the performance of *ETS-NLA*.

When *PTS* is applied with link adaptation, i.e., frame size optimization, the performance is considerably improved, however, we need to allocate some monitoring time for channel estimation. Monitoring causes some overhead, which is low for small number of links, but becomes significant and results in throughput degradation as the number of links is increased, especially when *PTS* is applied with *MA*. In *PTS-MA*, for high number of active

links, the time allocated for monitoring each link becomes low, which degrades the reliability of *MA*'s estimates. The estimation errors result in incorrect link adaptation and incorrect scheduling, so the throughput of *PTS-MA* keeps decreasing with increasing number of links and it even falls below *ETS-NLA* for  $M > 14$  links, as seen in Fig. 6. On the other hand, when *PTS* is applied with our IBEP estimation method, the high throughput of *PTS-CSI* is maintained irrespective of the number of active links. The throughput of *PTS-CSI* remains significantly above *PTS-MA* by up to 60%, due to the fact that *PTS-CSI* uses the fast and robust estimates provided by our proposed IBEP estimation method and it requires much lower monitoring overhead. The total throughput of *PTS-CSI* approaches 350 Mbps, improving system utilization to 73%, which is only 10% below *PTS-THEO* that uses perfect channel information. (100% efficiency is not possible due to fixed overhead of MAC and PHY layers.)

Since *PTS-CSI* achieves the highest throughput for a large range of number of connections, next, we compare the average throughput of individual links obtained by *PTS-CSI* and *ETS-NLA* algorithms, as depicted in Fig. 7. The error bars in this figure show the maximum and minimum link throughput values obtained by each scheme around their mean throughput values. For a low number of connections ( $M < 7$ ), *PTS-CSI* improves the average throughput of individual links by about 25% as compared to *ETS-NLA*. However, as the number of links is increased, the average per user data throughput of *ETS-NLA* is more than doubled with *PTS-CSI*. The error bars indicate that similar fairness is preserved by *PTS-CSI*, as compared to *ETS-NLA*, which by definition provides strict temporal fairness due to equal time allocations.

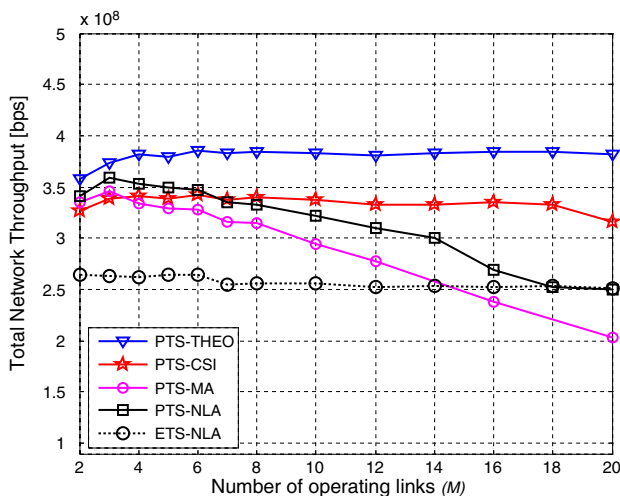


Fig. 6 Piconet’s total throughput versus the number of active links

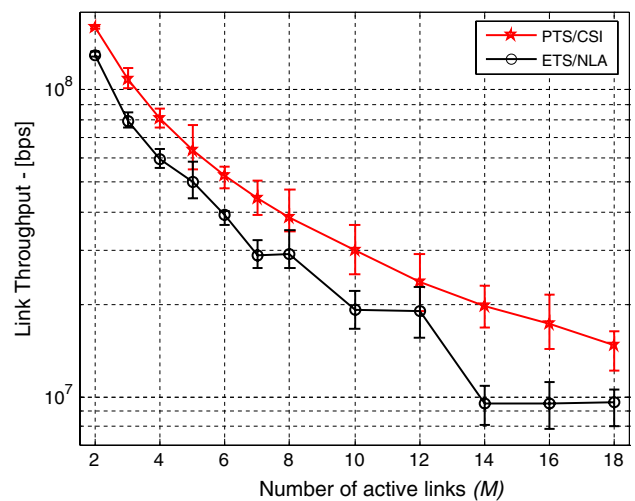


Fig. 7 Individual average link throughputs versus the number of active operating links

## 8 Conclusions

In this paper, we first propose a time scheduling method for MB-OFDM UWB WPANs, called *PTS*, where the channel time allocations of active links are determined based on link efficiency values. In order to enhance the system performance further, we then develop two cross-layer enhanced time scheduling methods: *PTS-MA* and *PTS-CSI*, which use Modiano's algorithm and our proposed technique for IBEP estimation, respectively. In both of these algorithms, the physical layer supplies IBEP estimates to the MAC layer, and these estimates are utilized in opportunistic multi link scheduling and optimal frame size adaptation.

Through detailed system simulations, we show that *PTS-CSI* stands out as a promising candidate for MB-OFDM based UWB WPANs, as it offers highest capacity with fair throughput distribution. *PTS-CSI* achieves this owing to its cross-layer structure and our proposed IBEP estimation method, which provides fast and robust estimates at the expense of very low monitoring overhead of just a single frame transmission.

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## Author Biographies



**Mehmet Keskinöz** got his M.S. and Ph.D. degrees from Electrical and Computer Engineering, Carnegie Mellon University, Pittsburgh (USA), in 1997 and 2001 respectively. In 2001, he joined to Electronics Engineering Program of Sabanci University Istanbul, Turkey where he is now an Associate Professor. His research interests include signal processing for wired and wireless communica-

tions, UWB communications, Multi-band OFDM UWB systems, Wireless Mesh Networks, magnetic and optical data storage systems, distributed detection and data fusion for wireless sensor networks, Turbo and LDPC coding, synchronization, digital watermarking. He is a recipient of Turkish NSF Research grant on distributed detection in wireless sensor networks and Career Award on wireless mesh networks in August 2005. He is a co-guest editor of *IEEE Communications Magazine* January 2009 Special Issue on Advances in Signal Processing for Wireless and Wired Communications. He is a member of IEEE Communication Society, IEEE Signal Processing Society and Optical Society of America.



**Ozgur Gurbuz** received her B.S. and M.S. degrees in Electrical and Electronics Engineering at Middle East Technical University, in 1992 and 1995, respectively. She received her Ph.D. degree in Electrical and Computer Engineering from Georgia Institute of Technology in 2000. From 2000 until 2002, she was a researcher and systems/algorithms engineer at Cisco Systems, San Jose, CA in Wireless Access and Wireless

Networking Business Units. She is currently an Associate Professor in the Faculty of Engineering and Natural Sciences at Sabanci University. Her research interests are in the field of wireless communications and networks, in particular medium access control, radio resource management, cross layer design, wireless networks with MIMO systems and smart antennas, wireless mesh networks and wireless sensor networks.



**Engin Masazade** got his B.S. degree from Electronics and Communications Engineering Istanbul Technical University 2003. He then obtained his M.S. degree from Sabanci University, Electronics Engineering Program in 2006 where he is now a Ph.D. candidate. During his M.S. and Ph.D. studies, he has been affiliated with Communication Theory and Technologies (CTT) Group under supervision of Dr. Mehmet Keskinöz. His research interests include bit-

error rate estimation and cross-layer design for Multiband OFDM systems, distributed detection, estimation, localization and tracking for wireless sensor networks.