Performance Evaluation of MB-OFDM based UWB System

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Abstract:

This paper investigates the Multi-band OFDM (MB-OFDM) based physical (PHY) layer proposal for IEEE 802.15.3a working group on short-range high data-rate Ultra-wide-Band (UWB) communications. An overview of the MB-OFDM PHY layer architecture with its various parameters is presented and the optimal choice of critical parameters is discussed. Next, we derive the theoretical un-coded Bit Error Rate (BER) of MB-OFDM over the Rayleigh fading channel. Performance results over realistic IEEE UWB channel models are analyzed and compared to a pulsed-OFDM based approach. Although pulsed-OFDM was presented in the literature as an enhancement to the MB-OFDM approach, simulation results showed that with same redundancy-factor, both systems give almost similar BER performance.

Keywords: Multi-band-OFDM, Pulsed-MB-OFDM, Ultra-wide-Band (UWB) Communications, Frequency Diversity.

1. Introduction

Recent advances in consumer electronics (camcorders, DVD players, wireless USB's etc.) have created a great need for wireless communications at very high data rates over short distances. Ultra-wide-Band (UWB) systems have shown their ability to satisfy such needs by providing data rates of several hundred Mbps [1].

In 2002, the Federal Communications Commission (FCC) allocated a large spectral mask from 3.1 GHz to 10.6 GHz for unlicensed use of commercial UWB communication devices [2]. Since then, UWB systems have gained high interest in both academic and industrial research community.

UWB was first used to directly modulate an impulse-like waveform with very short duration occupying several GHz of bandwidth. Two examples of such systems are Time-Hopping Pulse Position Modulation (TH-PPM) introduced in [3] and Direct-Sequence UWB (DS-UWB) [4]. Employing these traditional UWB techniques over the whole allocated band has many disadvantages including need for high complexity Rake receivers to capture multipath energy, high speed analog to digital converters (ADC) and high power consumptions. These considerations motivated a shift in UWB system design from initial 'single-band' radio that occupies the whole allocated spectrum in favor of 'multi-band' design approach [5].

'Multi-banding' consists in dividing the available UWB spectrum into several sub-bands, each one occupying approximately 500 MHz (minimum bandwidth for a UWB system according to FCC definition). By interleaving symbols across different sub-bands, UWB system can still maintain the same transmit power as if it was using the entire bandwidth. Narrower sub-band bandwidth also relaxes the requirement on sampling rates of ADCs consequently enhancing digital processing capability.

Multiband-OFDM (MB-OFDM) [5]-[6] is one of the promising candidates for PHY layer of short-range high data-rate UWB communications. It combines Orthogonal Frequency Division Multiplexing (OFDM) with the above multi-band approach enabling UWB transmission to inherit all the strength of OFDM technique which has already been proven for wireless communications (ADSL, DVB, 802.11, 802.16., etc.). For these reasons MB-OFDM was proposed as the PHY layer technology for UWB communication as part of IEEE 802.15.3a standardization process for Wireless Personal Area Network (WPAN) communications.

The objective of this paper is to investigate the performance of the MB-OFDM based PHY layer over

IEEE UWB channel models [7] and to make comparison with a competitive pulsed-MB-OFDM approach [8]. Optimal choice of some critical system parameters like Cyclic Prefix (CP) length and number of sub-carriers (IFFT/FFT size) is also discussed.

The next section gives a brief introduction to UWB technology. Section 3 presents the architecture and parameters of the MB-OFDM transceiver with discussion over optimal choice of parameters. Section 4 describes the UWB channel model proposed by IEEE channel modeling sub-committee that we used in our simulations. Section 5 gives the analytical probability of error analysis of MB-OFDM system over Rayleigh fading channels. BER performance results of MB-OFDM on various realistic UWB channel environments is given in section 6 with finally comparing the BER performance of Pulsed-MB-OFDM [8] approach to MB-OFDM system in section 7 and the conclusion in section 8.

2. UWB Definition

According to the FCC definition [1], a UWB device is any device where the fractional bandwidth is greater than 25% of its centre frequency or occupies 1.5 GHz, whichever is less. The fractional bandwidth is defined as $2(F_H - F_L)/(F_H + F_L)$ where F_H and F_L are the upper and lower frequency of the -10 dB emission level. The FCC recently approved [2] the deployment of UWB on an unlicensed basis in the 3.1–10.6 GHz band. The essence of this ruling is to limit the *Power Spectral Density* (PSD) measured in a 1–MHz bandwidth at the output of an isotropic transmit antenna to that shown in Fig. 1. The above spectral mask allows UWB-enabled devices to overlay existing systems while ensuring sufficient attenuation to limit adjacent channel interference. Additional PSD limits have been placed below 2 GHz to protect critical applications such as global positioning system (GPS) as shown. The first consequence of this spectral mask imposed by the FCC is to render the use of baseband pulse shapes difficult without additional transmit filtering to limit the out-of-band emission spectra.

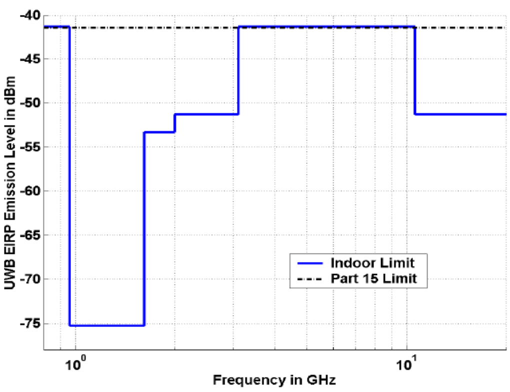

Fig. 1: UWB Spectral Mask

In summary, UWB communications is allowed at a very low average transmit power as compared to more conventional (narrowband) systems that effectively restricts UWB to short ranges. UWB is, thus, a candidate physical layer mechanism for IEEE 802.15 Wireless Personal Area Network (WPAN) for short-range high-rate connectivity that complements other wireless technologies in terms of link ranges.

3. Overview of MB-OFDM based PHY Layer

3.1. System Architecture and Parameters

A multi-band OFDM system [5]-[6]-[9] divides the available bandwidth into smaller non-overlapping sub-bands such that the bandwidth of a single sub-band is still greater than 500MHz (FCC requirement for a UWB system). The system is denoted as an 'UWB-OFDM' system because OFDM operates over a very wide bandwidth, much larger than the bandwidth of conventional OFDM systems. OFDM symbols are transmitted using one of the sub-bands in a particular time-slot. The sub-band selection at each time-slot is determined by a Time-Frequency Code (TFC). The TFC is used not only to provide frequency diversity in the system but also to distinguish between multiple users.

The proposed UWB system utilizes five sub-band groups formed with 3 frequency bands (called a band group) and TFC to interleave and spread coded data over 3 frequency bands. Four such band groups with 3 bands each and one band group with 2 bands are defined within the UWB spectrum mask (Fig. 2). There are also four 3-band TFCs and two 2-band TFCs, which, when combined with the appropriate band groups provide the capability to define eighteen separate logical channels or independent piconets. Devices operating in band group #1 (the three lowest frequency bands) are selected for the mandatory mode (mode #1) to limit RF phase noise degradations under low-cost implementations.

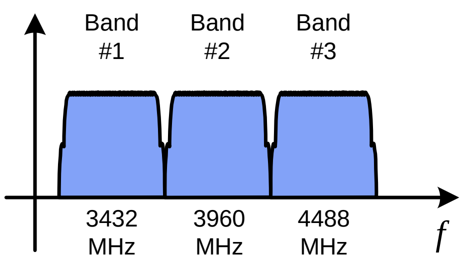

Fig. 2: UWB Spectrum Division into sub-bands

Fig. 2 gives an example of a TFC, where the available bandwidth of 1.584GHz (3.168-4.752 GHz) is divided into 3 sub-bands of 528MHz each.

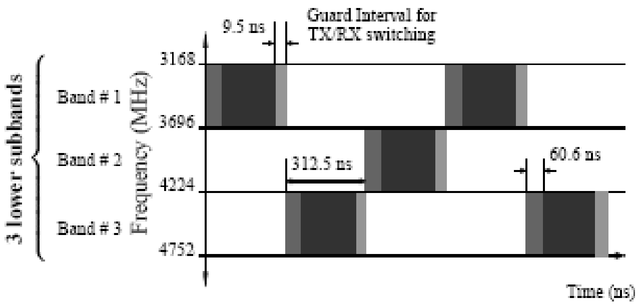

Fig. 3: Example of Time-Frequency Code in MB-OFDM system

There are many advantages associated with using the 'MB-OFDM' approach. This includes the ability to efficiently capture multi-path energy, simplified transceiver architecture, enhanced frequency diversity, increased interference mitigation capability and spectral flexibility to avoid low quality sub-bands and to cope with local regulations.

The TX and RX architecture of an MB-OFDM system is very similar to that of a conventional wireless OFDM system. The main difference is that MB-OFDM system uses a time-frequency kernel which provides TX with a different carrier frequency at each time-slot, corresponding to one of the center frequencies of different sub-bands. Fig. 3 shows the presence of a time-frequency kernel in a typical OFDM TX architecture.

In case of figure 3, time-frequency kernel produces carriers with frequencies of 3.432MHz, 3.960MHz and 4.488MHz, corresponding to center frequency of sub-band 1, 2 and 3.

The MB-OFDM based UWB PHY layer proposal [9] submitted to IEEE 802.15.3a working sub-committee for WPANs specifies parameters for different modules of PHY layer.

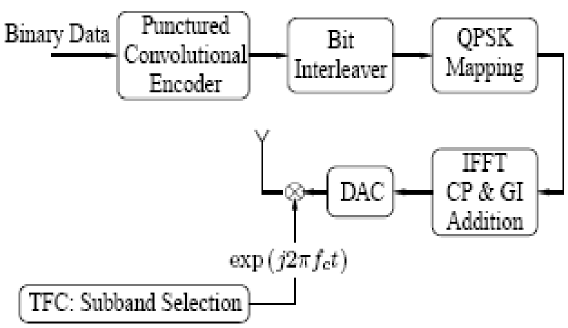

Fig. 4: TX Architecture of an MB-OFDM System

From the total available bandwidth of 7.5GHz (3.1-10.6 GHz), usage of 1.5GHz (3.1-4.75 GHz) is set mandatory for all MB-OFDM devices. Although sub-band bandwidth is required to be greater than 500 MHz (FCC requirement as stated earlier), hardware constraints impose using as narrow bandwidth as possible. Hence, a sub-band of 528 MHz was proposed in [6], because it can be generated using simpler synthesizer circuits.

To reduce hardware complexity, the internal precision of the digital logic and DAC was limited by using QPSK for constellation mapping. Different channel coding rates (using 1/3 convolution coding and puncturing), time and frequency domain spreading of factor 2, are employed to generate data rates of 55, 80, 110, 160, 200, 320 and 480 Mbps. Frequency-domain spreading, consists in transmitting twice the same information in a single OFDM symbol. It introduces a spreading factor of 2 and results in intra-sub-band frequency diversity. On the other hand, time-domain spreading is obtained by repeating the same OFDM symbol over different sub-bands and hence, it results in inter-sub-band frequency diversity.

A 128 point IFFT/FFT is used along with a short cyclic prefix (CP) length of 60.6 ns. Also, an additional guard interval of 9.5ns is added to allow the transmitter and receiver to switch from one sub-band to another. One OFDM symbol has a duration of $T_{SYM} = T_{FFT} + T_{CP} + T_{GI}$ where T_{FFT} is the FFT integration time, T_{CP} is the duration of the cyclic prefix and T_{GI} is the guard interval. This results in a total OFDM symbol duration of 312.5 ns occupying 528 MHz (fig. 3) which is sent through the UWB channel. Under the assumption that the cyclic prefix is long enough, no Doppler shift and linear hardware, the OFDM transmission chain can be modeled by the independent sub-carrier fading model. Then the received signal on sub-carrier k can be modeled with complex baseband representation as

$$Y_k = S_k H_k + n_k \qquad (1)$$

Where S_k is the transmitted QPSK modulated symbol, H_k is the k th coefficient of the channel FFT and n_k is the complex valued white gaussian noise. The receiver uses coherent detection with perfect channel estimates and QPSK constellation, which gives

$$R_k = Y_k H_k^* = S_k \left|H_k\right|^2 + n_k H_k^* \qquad (2)$$

where * denotes complex conjugate.

In the investigated MB-OFDM system, the information bit sequence is first encoded by a convolutional encoder. Then the encoded bits are interleaved by a random interleaver. The QPSK modulator creates the complex symbols sequence which are modulated by an OFDM modulator implemented by an IFFT. After adding cyclic prefix and guard interval, the time domain signal is sent through the UWB channel with respect to the TFC described above. The IEEE UWB channel model is supposed constant during the transmission of one packet and no time variability is present within one packet. For each packet a different channel realization is used within 100 channel realization. Fortunately, the UWB channel is highly frequency selective which creates the opportunity to use error control coding and frequency diversity techniques in order to increase the quality of service.

3.2. Optimal Choice of Critical Parameters

Two critical parameters in the MB-OFDM PHY layer, that greatly influence overall system complexity and performance, are the number of sub-carriers (N_{sub}) or FFT size and the cyclic prefix duration (T_{cp}). Here, we will try to find out their most suitable values for the MB-OFDM system.

N_{sub} must be set with respect to the factor $\beta = B_c / B_{sub}$, where B_c is the channel coherence bandwidth and B_{sub} is the sub-carrier bandwidth of the MB-OFDM system. β should be greater than 1 in order to allow flat-fading over each sub-channel. Table 1 provides the value of factor β calculated for different FFT sizes in all four IEEE proposed channel environments when the OFDM symbol occupies a bandwidth of 528 MHz in the frequency range of 3.1-4.75 GHz.

Table 1: Coherence to sub-carrier bandwidth ratio

Channel	**CM1**	**CM2**	**CM3**	**CM4**
B_c	8.9 MHz	8.25 MHz	4.5 MHz	2.7 MHz
β for 64 point FFT	1.078	1	0.545	0.327
β for 128 point FFT	2.157	2	1.09	0.6545
β for 256 point FFT	4.315	4	2.18	1.309

The above table clearly shows that β is always greater than 1 when a 256 point FFT is used. However, the number of complex multiplications per nanosecond for a 64, 128 and 256 point FFT are respectively 0.614, 1.433 and 3.27.

Since the MB-OFDM is targeted toward portable and handheld devices, an FFT size of 256 point is too complex for low-cost low-complexity solutions.

This shows that the best compromise between performance and complexity is made with an FFT size of 128, which is proposed in [9] and will be used below in our simulations.

The CP duration determines the amount of multi-path energy captured. Multi-path energy not captured during the CP window results in inter-carrier-interference (ICI). We will see in section 2.1 that the UWB channels are highly dispersive, a 4–10-m LOS channel environment has an rms delay spread of 14.28 ns, while the worst case channel environment (CM4) is expected to have an rms delay spread of 25 ns [7].

In [10], it was shown that the optimal value for CP duration in an OFDM system is equal to the delay spread of the channel. In order to minimize the impact of ICI and capture sufficient multi-path energy in MB-OFDM systems, the CP duration was chosen to be 60.6 ns (1/4th of useful symbol period) for all channel environments.

4. UWB Propagation Channel Model

In order to evaluate different PHY layer proposals, IEEE 802.15.3a channel modeling sub-committee proposed a channel model for realistic UWB environments [7]. During 2002 and 2003, the IEEE 802.15.3 Working Group for Wireless Personal Area
Networks and especially its channel modelling subcommittee decided to use the so called modified Sale–Valenzuela model (SV) [11] as a reference UWB channel model.
The real valued model is based on the empirical measurements originally carried out in indoor environments in 1987 (Saleh and Valenzuela, 1987). Due to the clustering phenomena observed at the measured UWB indoor channel data, the model proposed by IEEE 802.15 is derived from Saleh and Valenzuela using a log-normal distribution rather than an original Rayleigh distribution for the multi-path gain magnitude. An independent fading mechanism is assumed for each cluster as for each ray within the cluster. In the SV models, both the cluster and ray arrival times are modelled independently by Poisson processes.

The multi-path channel impulse response can be expressed as

$$h(t) = \lambda \sum_{l \geq 0} \sum_{k \geq 0} \alpha_{k,l} \delta(t - T_l - \tau_{k,l}) \qquad (3)$$

Where $\alpha_{k,l}$ is the real-valued multi-path gain for cluster l and ray k. The l th cluster arrives at time T_l and its k th ray arrives at $\tau_{k,l}$ which is relative to the first path in cluster l, i.e. $\tau_{0,l} = 0$. The amplitude $|\alpha_{k,l}|$ has a log-normal distribution and the phase $\angle \alpha_{k,l}$ is chosen from $\{0, \pi\}$ with equal probability.

Due to the fact that the log-normal shadowing of the total multi-path energy is captured by the term λ, the total energy contained in the terms $\alpha_{k,l}$ is normalized to unity for each realization. Four different channel implementations are suggested, which are based on the average distance between transmitter and receiver, and whether a LOS component is present or not (CM1, CM2, CM3, CM4). The four channel models and their parameters are listed in Table 2. Figure 5 gives an example of 100 channel realizations that are based on CM3 model. The delay resolution in the models is 167 ps, which corresponds to a spatial resolution of 5 cm.

Table 2: IEEE UWB channel model characteristics

Channel	**CM1**	**CM2**	**CM3**	**CM4**
Mean excess delay (ns)	5.05	10.38	14.18	-
RMS delay (ns)	5.28	8.03	14.28	25
Distance (m)	0-4	0-4	4-10	10
Scenario	LOS	NLOS	LOS	NLOS
No. of significant paths (85%)	20.8	33.9	64.7	123.3

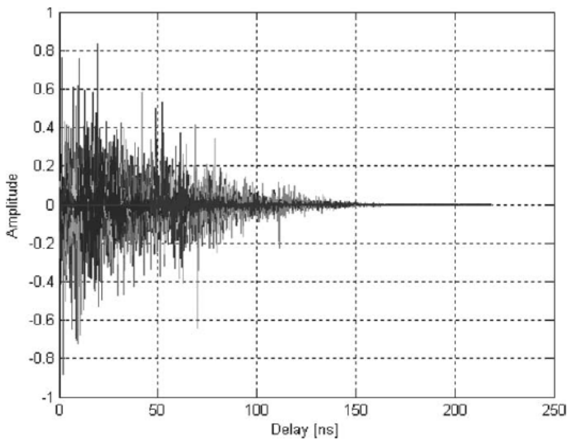

Fig. 5: Delay profiles of CM3 channel, 100 channel realizations

5. Theoretical BER Analysis of Un-coded MB-OFDM Systems

In this section the theoretical analysis of the probability of bit error of an OFDM system in a multi-path channel is performed. It is well known that in an AWGN channel the bit error probability of an OFDM system with QPSK modulation is given by

$$P_e\left(\frac{E_b}{N}\right) = \frac{1}{2}\text{erfc}\left(\sqrt{\frac{E_b}{N}}\right) \tag{4}$$

However, it is necessary to determine the performance in a multi-path channel and take into account the fading introduced by the channel. If the length of the cyclic-prefix introduced in the OFDM symbol is larger than the delay spread of the channel, then the received symbol can be represented by

$$y_e = H_e(f_n)\sqrt{2E_b}\,c_l + n_e \tag{5}$$

Hence, by symmetry equation (5) becomes

$$P_e\left(|H_e(f_n)|^2\frac{E_b}{N}\right) = \frac{1}{2}\text{erfc}\left(\sqrt{|H_e(f_n)|^2\frac{E_b}{N}}\right) \tag{6}$$

To simplify notations, we normalize the energy contained in the channel and given by

$$\eta = |H_e(f_n)|^2 \tag{7}$$

Thus, normalization implies

$$\mathbb{E}[\eta] = \mathbb{E}\left[|H_e(f_n)|^2\right] = \mathbb{E}\left[\sum_k \alpha_k^2\right] = 1$$

The energy per bit at the receiver end, is denoted by $\mathcal{E}$ which is given by

$$\mathcal{E} = \eta E_b$$

Thus equation (4) becomes

$$P_e\left(\frac{\mathcal{E}}{N}\right) = \frac{1}{2}\text{erfc}\left(\sqrt{\frac{\mathcal{E}}{N}}\right) \tag{8}$$

This gives us the error probability over one sub-carrier and for one specific realization of the channel. In order to take an average performance measure in a multi-path channel, we are required to take the mean of this error probability over all the possible channel realizations. The mean error probability function can thus be represented by

$$\bar{P}_e\left(\frac{\mathcal{E}}{N}\right) = \mathbb{E}\left[P_e\left(\eta\frac{\mathcal{E}}{N}\right)\right] = \frac{1}{2}\int_0^\infty \text{erfc}\left(\sqrt{\eta\frac{\mathcal{E}}{\text{N}}}\right)p_\eta(\eta)\,\text{d}\eta \tag{9}$$

Where $p(\eta)$ is the probability density function of the variable n.

The frequency domain coefficients of the channel $H(f)$ follow the Rayleigh fading law. The variable η hence follows an exponential decay. Assuming that the mean of the variable η is equal to 1, its probability density function is given by

$$p_\eta(\eta) = \exp(-\eta)$$

The mean probability of error thus becomes

$$\bar{P}_e\left(\frac{\mathcal{E}}{N}\right) = \frac{1}{2}\int_0^\infty \text{erfc}\left(\sqrt{\eta\frac{\mathcal{E}}{\text{N}}}\right)\exp(-\eta)\,\text{d}\eta \tag{10}$$

By solving the above integration by parts and knowing that erfc (∞) =0 and erfc (0) =1, we obtain the result

$$\bar{P}_e(\frac{\mathcal{E}}{N}) = \frac{1}{2} - \frac{1}{2\sqrt{1+\frac{1}{\mathcal{E}/N}}} \qquad (11)$$

We will use this expression to trace the theoretical error probability curve for an Un-coded MB-OFDM system in a Rayleigh fading channel. The theoretical probability of bit error was compared with the simulation results for CM1 channel in figure 6. BER obtained from simulation was found to be very close to the theoretical probability of bit error suggesting that the high number of multi-paths in an indoor environment renders the indoor channel closeness to the Rayleigh fading model.

6. MB-OFDM Performance Analysis in Different UWB Channel Scenarios

In this section the performance of the MB-OFDM based PHY layer is evaluated over different indoor UWB channel scenarios as defined in the previous sub-section.

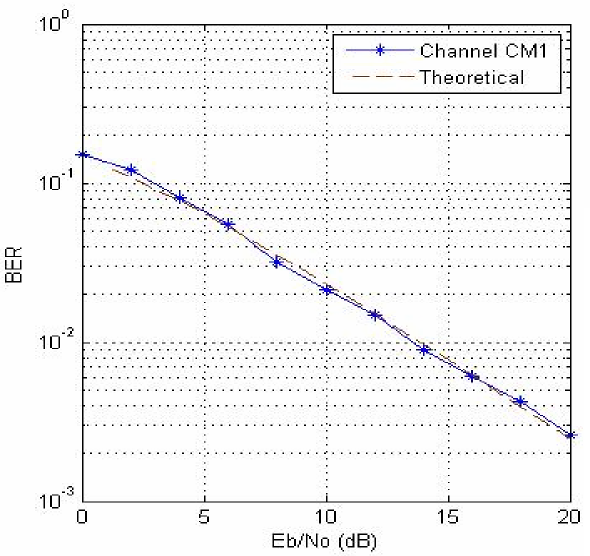

Fig. 6: Theoretical and simulated BER of Un-coded ME OFDM over Rayleigh (theoretical) fading and CM1 (simulation) channels.

We simulated mode 1 of the MB-OFDM based PI layer proposal [9]. This mode employs three sub-bands 528 MHz (3.1-4.684 GHz). All simulation results w obtained using a transmission of at least 500 packets w a payload of 1024 bytes each. The proposal is targeting data transmission at rates of 110 Mbps over 10 meters, 220 Mbps over 4 meters and 480 Mbps over 1 meter [12]. The BER must be less than 10^{-5} in order to achieve a packet error rate less than 8 % as required in [12]. The channel is supposed to be time-invariant during transmission of one packet but changes from packet to packet. Punctured convolutional codes with rate 11/32, ½ and ¾, combined with time and frequency domain spreading, were used in order to achieve three (55,160 and 480 Mbps) out of eight data-rates proposed in [9].

In our simulations, when there is no diversity (480 Mbps), a one-tap frequency-domain equalizer is used at the receiver, like that of a conventional OFDM system. However, when frequency-diversity is exploited in the system, Maximal Ratio Combining (MRC) technique [13] is used to combine different diversity branches. Then, a soft Viterbi decoder followed by a de-interleaver is used to recover the binary data.

In 55 Mbps mode, MB-OFDM system enjoys both intra and inter-sub-band frequency diversity. This combined with powerful channel coding rate (11/32) and bit-interleaving, makes the system robust to a frequency-selective channel but at the cost of reduced data-rate.

In medium data-rate (160 Mbps) mode, the system uses only inter-sub-band diversity which provides higher data-rate but degrades BER performance, compared to 55 Mbps mode. Further performance degradation can be observed for 480 Mbps data-rate mode, where neither intra nor inter-sub-band diversity is available.

These observations were verified by means of extensive simulations. Here, we report simulation results over CM1 and CM4 channel scenarios as shown in figures 7 and 8 respectively. Similar behavior for different data-rates was observed for CM2 and CM3 channel scenarios.

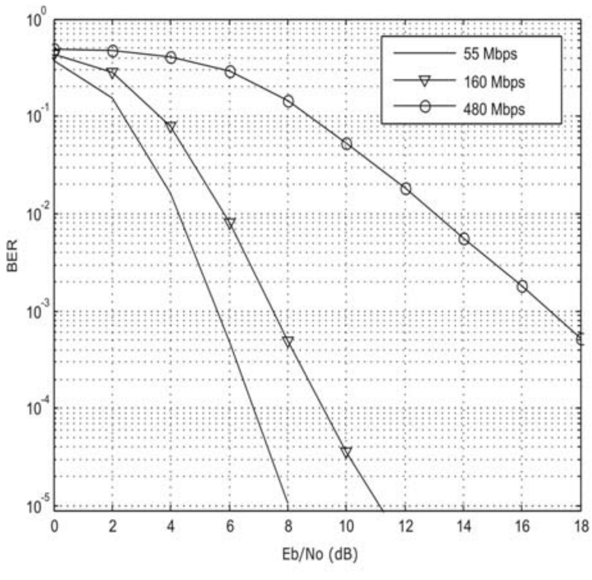

Fig. 7: MB-OFDM over CM1

Interesting performance results were observed for lowest (55 Mbps) and highest (480 Mbps) data-rate mode, in various channel scenarios. The inherent high frequency-selective nature of UWB channels can be exploited in a positive way by using different diversity-combining techniques. This was observed in the most robust mode (55 Mbps), where channel diversity was fully exploited by employing MRC technique. Thus the MB-OFDM performs better in the CM4 channel environment than in the CM1 channel thanks to its inherent frequency diversity as shown in figure 9. These results comply with those presented in [14]. In 480 Mbps mode, a different behavior was observed. The performance in CM1 was found to be better than in CM4. This is due to the absence of time and frequency-domain spreading and low coding rate that prevents the exploitation of channel diversity. This leads to worst BER results for 480 Mbps mode in all channels as shown in figure 9.

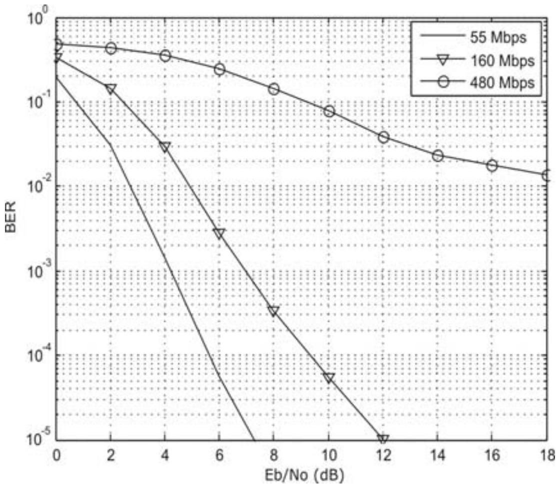

Fig. 8: MB-OFDM over CM4

7. Multiband Pulsed-OFDM Versus MB-OFDM

7.1. Multiband Pulsed-OFDM System

Multiband pulsed-OFDM uses orthogonal 'pulsed' sub-carriers, instead of continuous sub-carriers [8]. Pulsed OFDM signal is generated by up-sampling the digital OFDM symbol after IFFT block. Up-sampling is done by inserting $K-1$ zeros between samples of the signal. K can be termed as the 'redundancy-factor' of the pulsed OFDM system.

The up-sampled signal is fed into a D/A converter and sent over the channel.

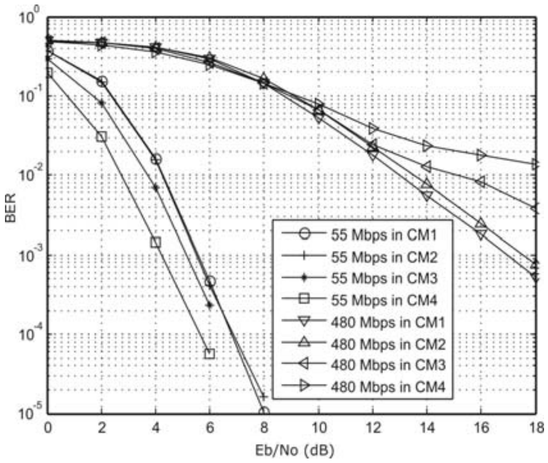

Fig. 9: Performance of 55 and 480 Mbps modes over different IEEE channel models

As reported in [15], up-sampling a signal in time domain by factor K results in its K time repetition in frequency-domain. Hence, pulsed-OFDM provides K diversity branches which can be combined together using any diversity combining technique (MRC, EGC, etc.), to enhance system performance in dense multi-path UWB channels. Clearly, this approach has the potential of simulating large OFDM systems (i.e. with a large number of sub-carriers) while actually using short FFT's, the ratio being the redundancy factor. The corresponding constraint is that the various groups of sub-carriers that are commuted are now interleaved.

7.2. Performance Comparison

A BER performance comparison is made between MB-OFDM and pulsed-MB-OFDM system, both operating at 55 Mbps. For pulsed-MB-OFDM system, 128 sub-carriers were obtained by up-sampling a 32 sub-carrier OFDM symbol with a redundancy-factor of $K = 4$. The 55 Mbps mode of MB-OFDM system was used with intra and inter-sub-band diversity which provide an overall redundancy-factor of 4. MRC was used in both of the systems to combine the 4 available diversity branches. The signal bandwidth was set to 528 MHz in order to maintain the same spectral efficiency. Figure 10 shows the BER results of MB-OFDM and pulsed-MB-OFDM systems over the CM4 channel.

From this figure we observe that for low SNR values, both systems perform equally, however, for large SNR values, pulsed-MB-OFDM system gradually starts to perform better. The basis of Pulsed-MB-OFDM approach is to exploit the diversity in frequency domain. However, this diversity can only be exploited at low data-rates because high data-rates are achieved by less frequency diversity exploitation.

A comparison between the above two systems has already been made in [8]. However, that comparison was made between a Pulsed-MB-OFDM system with $K = 4$ and an MB-OFDM system with $K = 2$.

In our comparisons, both systems have the same redundancy-factor which ensures a fair comparison.

Our observations show that using pulsed-MB-OFDM does not improve so much system performance in terms of BER compared to a robust MB-OFDM mode (almost a gain of 0.3 dB). Further, pulsed approach can only be used in low data rate applications because whenever diversity is exploited, the useful data rate is divided by the redundancy-factor.

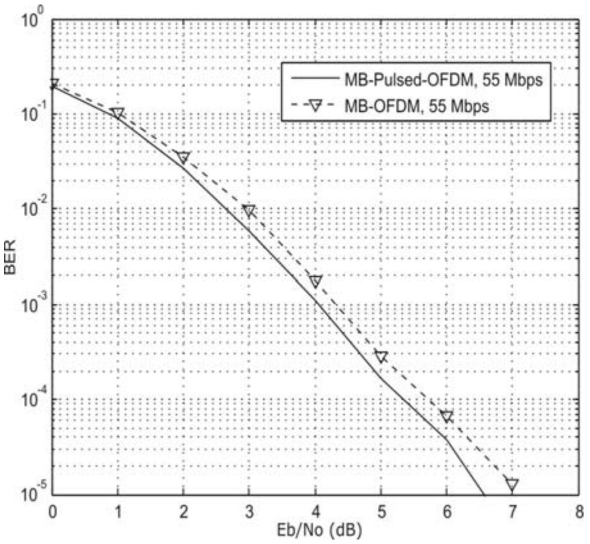

Fig. 10: Performance comparison of MB-OFDM and Pulsed-MB-OFDM for $K = 4$

8. Conclusion

MB-OFDM system presents a very good technical solution to be used as UWB PHY layer for short-range high data-rate wireless applications. Performance results were obtained by simulating an MB-OFDM system over various realistic UWB channel scenarios. We also derived the theoretical BER of Un-coded MB-OFDM over Rayleigh fading channels and compared it with simulation results. It was found that severe indoor UWB propagation environments like CM4, being highly frequency-selective in nature, necessitate the usage of diversity combining techniques to achieve target BER of 10^{-5}. Also performance comparison was made with another approach (pulsed-MB-OFDM). Moreover, we observed that the performance improvement of pulsed-MB-OFDM is not considerable compared to MB-OFDM system.

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