Performance Analysis of MB-OFDM in the Presence of Multiple UWB Interferers

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***Abstract*— Ultra wideband (UWB) technology is one of the promising solutions for future short-range communication which has recently received a great attention by many researchers. So far, two standards have been proposed to the IEEE 802.15.3a task group (TG3a) as a high-speed physical technology for next-generation wireless personal area networks (WPAN). These technologies are multiband orthogonal frequency division multiplexing (MB-OFDM) UWB and direct-sequence (DS) UWB; two incompatible standards which, due to the withdrawal of the standardization process, will have to coexist in the near future. In this paper, we present a performance analysis of MB-OFDM UWB communication in the presence of binary phase shift keying time-hopping (BPSK-TH) UWB and BPSK-DS UWB interfering transmissions. In the bit error rate (BER) analysis, it is considered that there are multiple UWB interferers affecting the MB-OFDM signal. A Gaussian approximation is considered for the multiple UWB interferers under consideration, and the BER performance is evaluated for a multiband OFDM UWB system and the WLAN 802.11a singleband OFDM-based standard. Numerical results and comparisons are provided for different OFDM and UWB coexisting systems.**

***Index Terms*— MB-OFDM, 802.11a, UWB, coexistence, multiple interferers**

I. Introduction

Ultra wideband (UWB) technology has gained significant attention in recent years especially after year 2002 when the US Federal Communication Commission (FCC) opened the frequency range, from 3.1GHz to 10.6GHz, for unlicensed operation of UWB radio. Two standards for UWB communication have been proposed to the IEEE 802.15.3a task group (TG3a), namely, multiband orthogonal frequency division multiplexing (MB-OFDM) UWB [1] and direct-sequence (DS) UWB [2]. After many discussion sessions for choosing one of these two standards, no single decision has been reached and accordingly both systems will have to coexist in the near future. Many works have been done so far regarding the interference issue in UWB communication, ranging from analyzing the mutual interference effects between different narrowband (NB) and UWB systems [3]–[8] to investigating the impact of other interference sources caused by, for example, multipath and multiuser communication on UWB systems [9]–[12]. For instance, in [13], a review of the multiple interference cancellation techniques for UWB is presented. However, an analysis of the coexistence issue of the aforementioned UWB standards has not been done so far, and most related works have focused on the coexistence between NB and UWB systems, considering DS UWB or time-hopping (TH) UWB but not the MB-OFDM structure of the UWB signal.

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Previous works related to coexistence of the two UWB standards are reported in [15] and [16]. In [15], the authors use a multi-carrier template waveform for mitigating the effect of MB-OFDM interference on a pulse based p-UWB system; this work does not include an analytical modelling of the effect of MB-OFDM interference and does not take into consideration the reverse case which pertains to the effect of p-UWB interference onto the MB-OFDM UWB system. On the other hand, a closer look to [15] reveals that a simple pulse model for an UWB system is not sufficient for studying the effect of interference on the UWB system as a victim receiver. In [16] the authors simulated the MB-OFDM UWB and DS UWB standards to study the effect of the mutual interference between both systems, and proposed to reduce the interference by means of power control techniques. However, because of its importance, MB-OFDM UWB communication needs further research especially in the context of its coexistence with other UWB systems.

In this work, we analyze the effect of two UWB systems (BPSK-TH and BPSK-DS) on the performance of the MB-OFDM UWB standard in terms of bit error rate (BER), using a procedure similar to that used in [14] for validating the 802.11a/UWB coexistence. The analysis takes into account the number of interfering pulses from either of the two UWB systems (DS or TH) to the MB-OFDM UWB standard, is done in a multi-interferer scenario, and supported by results provided to compare the system's performance for different number of interferers. Furthermore, because of the similarity between MB-OFDM and the WLAN 802.11a physical layer standard, which also uses OFDM at the physical layer, BER results pertaining to the coexistence between UWB systems and the 802.11a OFDM-based standard are also provided and compared with MB-OFDM.

The remainder of this paper is organized as follows. In Section II, the models of the OFDM and UWB signals under study are provided. Section III analyzes the interference term of the two UWB systems (TH and DS) on the OFDM-based systems under consideration. Section IV presents numerical results illustrating the BER performance of the 802.11a OFDM and MB-OFDM systems and their comparison in the presence of multiple UWB interferers. Finally, concluding remarks are drawn in section V.

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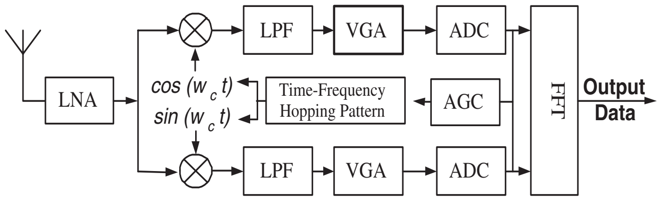

Fig. 1. Receiver architecture for a MB-OFDM system

II. Signals and systems models

In this section, the model for the OFDM-based receiver is presented along with the OFDM and UWB signal models.

A. MB-OFDM System Model

The example of a receiver architecture for a MB-OFDM system is shown in Fig. 1. Input data is coded and grouped into symbols. The symbol generator outputs complex symbols of duration T_s. The set of symbols $\{a_i(n), 0 \le n \le N-1\}$ is then modulated by the N-point IDFT (implemented with FFT) onto N subcarriers at the ith block interval. These symbols are now independent and identically distributed (i.i.d.). After a guard interval is inserted, which purpose is to reduce the interference between blocks, the transmitted sequence of the ith block can be written as:

$$s_i(k) = \sqrt{2P_{TC}} \sum_{n=0}^{N-1} a_i(n) e^{\frac{j2\pi nk}{N}} \text{ for } -G \le k \le N-1, \quad (1)$$

where the first G elements are the guard samples which are the summation of the cyclic prefix and the guard interval, $\sqrt{2P_{TC}}$ is the transmit power for the MB-OFDM system and $s_i(k)$ is assumed to be zero for $k < -G$ and $k \ge N$. The total transmitted sequence at base band can be written as:

$$s(k) = \sum_{i=-\infty}^{+\infty} s_i(k - i(N+G)). \quad (2)$$

Later, an RF carrier is inserted and the signal is taken to the specified carrier frequency with respect to the frequency-hopping pattern of the MB-OFDM system [17]:

$$s_{RF}(t) = Re\left\{ \sum_{i=-\infty}^{+\infty} s_i(k - i(N+G)) e^{-j2\pi(f_c + f_{MB}[i])t} \right\}, \quad (3)$$

where f_c is a constant frequency offset and $f_{MB}[i] \in \{(n_b - 1)N\Delta_F | n_b \in \{1, 2, ..., N_B\}\}$ is the additive periodic value used to switch between the N_B MB-OFDM frequency bands with Δ_F the MB-OFDM system subcarrier's bandwidth. Here we consider the processing of the MB-OFDM signal at base band.

B. UWB System Model

The BPSK-TH UWB signal for the kth UWB transmitter can be expressed as:

$$s_{TH}^{(k)}(t) = C_T \sum_{i=-\infty}^{+\infty} d_{\lfloor i/N_s \rfloor}(k) g(t - iT_F - c_i^{TH}(k) T_c), \quad (4)$$

while for the BPSK-DS UWB we have:

$$s_{DS}^{(k)}(t) = C_T \sum_{i=-\infty}^{+\infty} \sum_{n=0}^{N_c-1} d_i(k) c_n^{DS}(k) g(t - iT_F - nT_c), \quad (5)$$

where t is the time index and $g(t)$ is the pulse waveform, with Fourier transform $G(\omega)$ and normalized such as $\int_{-\infty}^{+\infty} g^2(t)dt = 1$ [17]. In (4) and (5), C_T denotes the transmitted power, N_s corresponds to the number of pulses used to transmit a single information bit in TH-UWB, which is practically the length of the repetition code, and N_c is the number of chips per information bit in DS-UWB. The sequence $\{c_i^{TH}\}$ represents the TH code, which is pseudorandom and takes on values in the range $0 \le c_i \le N_h$ where N_h is the number of hops. $\{c_i^{DS}\}$ represents the spreading signature sequence, T_F is the time duration of a frame, T_c is the hop width which satisfies $N_h T_c = T_F$, and the bit duration is given by $T_{bit} = N_s T_F$. Finally, d_i represents the ith binary data bit transmitted.

III. Analyzing the UWB Interference Term

In this section, the general expression for the MB-OFDM received signal is presented and the UWB interference term is formulated. The OFDM received signal is given by

$$r(t) = s_R(t) + I_{UWB}(t) + n(t), \quad (6)$$

where $s_R(t)$ is the received signal for the nth OFDM symbol, $I_{UWB}(t)$ is the interfering signal and $n(t)$ is the receiver noise. Assuming N_u interfering UWB users transmitting asynchronously, the interference term can be written as

$$I_{UWB}(t) = \sum_{k=1}^{N_u} A_k I_{UWB}^{(k)}(t - \tau_k), \quad (7)$$

where $I_{UWB}^{(k)}(t)$ can be the BPSK-TH (4) or BPSK-DS (5) UWB signal, A_k represents the channel gain for each interfering signal, and τ_k represents time shifts which account for users asynchronism. Here we follow the same procedure as in [14] to derive the interference term. With respect to Fig. 1, the in-phase (I) and quadrature (Q) components of a single UWB interfering pulse after multiplying to the local oscillator and passing through the lowpass filter are given by [14]:

$$\begin{aligned} I(t) &= [g(t) \times \cos(\omega_c t + \varphi)] * h_0(t), \\ Q(t) &= [g(t) \times -(\sin(\omega_c t + \varphi))] * h_0(t), \end{aligned} \quad (8)$$

where the asterisk (*) indicates the convolution, $h_0(t)$ is the impulse response of the lowpass filter and φ is the random phase for the local oscillator. After taking the inverse Fourier transform of $I(\omega)$, the in-phase element of the received UWB pulse is given by [14]:

$$P_I(t) = \frac{1}{2\pi} \int_{-\pi B}^{\pi B} \frac{1}{2} [e^{j\varphi} G(\omega - \omega_c) + e^{-j\varphi} G(\omega + \omega_c)] \times H_0(\omega) e^{j\omega t} d\omega, \quad (9)$$

where B is the baseband filter bandwidth. For $B \ll \omega_c/2\pi$, the ω_c term within G in (9) being dominant with respect to

ω, it follows that G terms evaluate to their values at $\omega = 0$. Hence, (9) reduces to:

$$P_I(t) = \frac{1}{2}[e^{j\varphi}G(-\omega_c) + e^{-j\varphi}G(\omega_c)]\frac{1}{2\pi}\int_{-\pi B}^{\pi B} H_0(\omega)e^{j\omega t}d\omega$$
$$= \frac{1}{2}[e^{j\varphi}G(-\omega_c) + e^{-j\varphi}G(\omega_c)]h_0(t). \tag{10}$$

Similarly, for the $P_Q(t)$ we have:

$$P_Q(t) = \frac{j}{2}[e^{j\varphi}G(-\omega_c) - e^{-j\varphi}G(\omega_c)]h_0(t). \tag{11}$$

Now for the case of a train of BPSK-TH UWB pulses at baseband, the resulting interference is given by:

$$z^{(k)}_{I,UWB}(t) = C_R \sum_{i=-\infty}^{+\infty} d_{\lfloor i/N_s \rfloor}(k)P_I(t - iT_F - c^{TH}_i(k)T_c),$$
$$z^{(k)}_{Q,UWB}(t) = C_R \sum_{i=-\infty}^{+\infty} d_{\lfloor i/N_s \rfloor}(k)P_Q(t - iT_F - c^{TH}_i(k)T_c), \tag{12}$$

where C_R is the received power. I and Q samples of the UWB interference are given by $z^{(k)}_{I,UWB}(m\Delta_T)$ and $z^{(k)}_{Q,UWB}(m\Delta_T)$ where $\Delta_T = 1/N\Delta_F$. Note that the index i in (12) does not go from minus infinity to plus infinity given that only a limited number of UWB pulses will contribute to the interference generated onto the MB-OFDM receiver. These pulses are those which arrive within one baseband filter period $(1/B)$ on either side of the MB-OFDM symbol. We can calculate a range for index i in (12) according to [14]: $-L_1 \le i \le L_2 - 1$ where $L_1 \approx \lfloor 1/BT_F \rfloor$ and $L_2 = L_1 + M_u$ with $M_u = \lceil N.\Delta_T/T_F \rceil = \lceil 1/\Delta_F T_F \rceil$, where $\lfloor . \rfloor$ denotes upper integer rounding. Note that T_F should be replaced by T_c for the BPSK-DS UWB case.

Now we consider an auxiliary variable defined by $\xi_l(k) = lT_F + c_l(k)T_c$ to simplify the notation in the following equations. The contribution of the kth UWB interfering signal to the ith OFDM output is found as follows [14]:

$$U^{(k)}_i = \frac{1}{N}\sum_{m=0}^{N-1}(z^{(k)}_{I,UWB}(m\Delta_T) + jz^{(k)}_{Q,UWB}(m\Delta_T))e^{\frac{-j2\pi mi}{N}}$$
$$= \frac{C_R}{N}\sum_{m=0}^{N-1}\sum_{l=-L_1}^{M_u-L_1+1} d_{\lfloor l/N_s \rfloor}(k)[P_I(m\Delta_T - \xi_l(k))$$
$$+ jP_Q(m\Delta_T - \xi_l(k))]e^{\frac{-j2\pi mi}{N}} \tag{13}$$

where $c_l(k)$ corresponds to either $c^{TH}_l(k)$ or $c^{DS}_l(k)$. Then, using (10) and (11) and doing the necessary mathematical manipulations we obtain [14]:

$$U^{(k)}_i = C_R e^{j\varphi}G(\omega_c)H_0(2\pi f)\sum_{l=-L_1}^{M_u-L_1+1} d_{\lfloor l/N_s \rfloor}(k)e^{-j2\pi i\Delta_F \xi_l(k)} \tag{14}$$

As observed, the expected value of (14) is equal to zero and the variance of the kth interfering signal can be shown to be given by:

$$\sigma^2_{I^{(k)}_{UWB}} = E\left\{|U^{(k)}_i|^2\right\}$$
$$= C_R|G(\omega_c)|^2 E\left\{\sum_{l=-L_1}^{M_u-L_1+1} d_{\lfloor l/N_s \rfloor}(k)e^{-j2\pi i\Delta_F \xi_l(k)}\right\}$$
$$= (M_u + 2L_1)C_R|G(\omega_c)|^2, \tag{15}$$

where we consider $|G(\omega_c)|^2 = 1$. As for the BPSK-DS UWB case, the same formula for the variance of the interference term applies except that the summation limits in (15) are obtained by replacing T_F with T_c as previously mentioned.

Having derived the necessary term for the variance of the UWB interference signal, we can express the bit error probability for the MB-OFDM system with QPSK modulation as:

$$P_{e,QPSK} = Q\left(\sqrt{\frac{P_{RC}}{\sigma^2_n + \sigma^2_{I_{UWB}}}}\right), \tag{16}$$

where $Q(a) = \int_a^\infty \frac{1}{\sqrt{2\pi}}e^{-x^2/2}dx$ is the complementary probability distribution function for the Gaussian distribution, P_{RC} is the received power of the OFDM system and $\sigma^2_n = N_0\Delta_F$ [14].

IV. Numerical Results

We now provide numerical results considering a worst case scenario where the UWB interference is always present in the environment. Equation (16) is the expression for the BER at one FFT bin output of the receiver, for other bins the error is uniformly distributed. In our analysis, we consider a MB-OFDM system with 128 subcarriers, each with a spacing of 4.125 MHz. Three bands of operation are defined for a mode 1 device, with center frequencies at 3432 MHz, 3960 MHz and 4488 MHz. The MB-OFDM system hops between these three bands based on a special pattern [1]. We also present results for a 802.11a WLAN system with 64 subcarriers, each with a bandwidth of 0.3125 MHz. The carrier frequency is 5.22GHz. Furthermore, it is assumed that the guard interval is long enough for the intersymbol interference to be cancelled, and we consider the initial phase of the local oscillator to be zero ($\varphi = 0$). As for the TH and DS UWB systems considered for the numerical analysis, the frame duration (T_F) and the hop width (T_c) are chosen to be 1ns and 0.0625ns respectively. The number of hops (N_h) equals 16.

Fig. 2 and Fig. 3 show the average BER versus E_b/N_0 of the MB-OFDM system and the WLAN 802.11a system, respectively. For different numbers of UWB interferers, each interferer is assumed to be located at the same distance from the OFDM reciever. It is observed that DS UWB interference causes more degradation than TH UWB interference. Indeed, for the DS UWB case the pulse repetition time T_c is less than T_F (Pulse repetition time for TH UWB), which implies that more interfering pulses will affect the OFDM system's performance. Another issue is the effect of the number of UWB interferers. As expected, the performance deteriorates as the number of interferers increases. Fig. 2 also shows that for the MB-OFDM system there is no much difference between the effect of DS UWB and TH UWB interferences especially when the number of interferers is low.

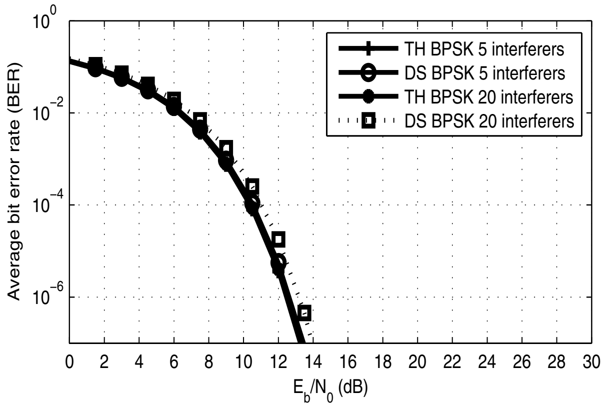

Fig. 2. Average BER versus E_b/N_0 of the MB-OFDM system in the presence of TH and DS UWB interference

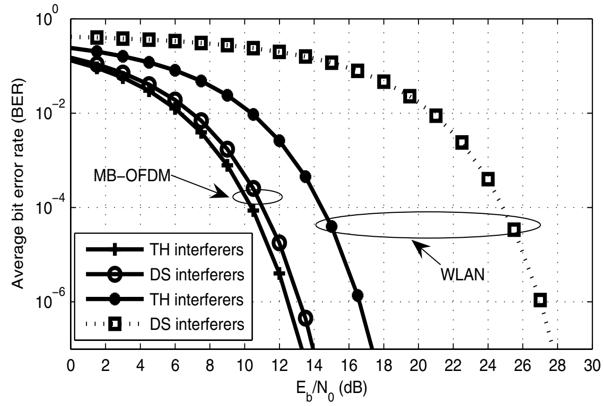

Fig. 4. Comparison of the BER performance between 802.11a OFDM and MB-OFDM in the presence of $N_u = 20$ interferers

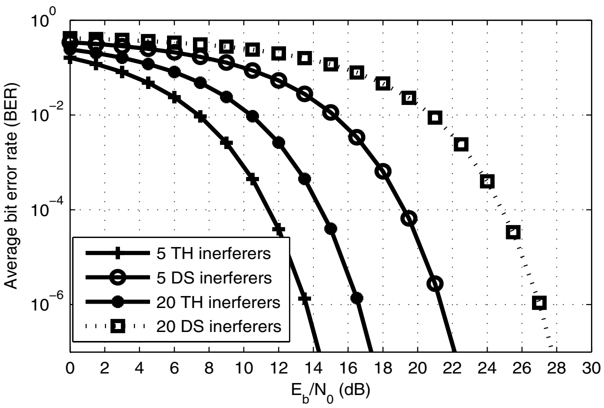

Fig. 3. Average BER versus E_b/N_0 of the WLAN 802.11a system in the presence of TH and DS UWB interference

Finally, Fig. 4 shows a comparison of BER performance between 802.11a OFDM and MB-OFDM. As can be seen, the MB-OFDM system is less vulnerable to UWB interference as opposed to the 802.11a OFDM system. Indeed, shorter symbol period in MB-OFDM causes less UWB interfering pulses to pass through the receiver filter. However, when the interferers are much closer to the MB-OFDM system or that they are greater in number, the performance of the MB-OFDM system can also degrade severely.

V. Conclusion

The impact of UWB interference on the BER performance of 802.11a OFDM and MB-OFDM systems was studied. Two different UWB systems, namely TH and DS, were considered in the performance analysis. It was realized that DS UWB interference causes more degradation compared to TH UWB interference. The number of UWB interferers is also an issue which can significantly affect the performance of the OFDM systems. Both OFDM standards were compared as well, showing that 802.11a WLAN OFDM is more sensitive to UWB interference compared to MB-OFDM. Ongoing work includes designing the UWB system parameters to dynamically adapt to the transmission environment for the purpose of limiting the resulting interference on MB-OFDM systems and facilitating the coexistence of these two standards.

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