Adaptive multi-carrier spread-spectrum with dynamic time-frequency codes for UWB applications

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ADAPTIVE MULTI-CARRIER SPREAD-SPECTRUM WITH DYNAMIC TIME-FREQUENCY CODES FOR UWB APPLICATIONS

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Abstract: In this paper, we propose a spread spectrum multi-carrier multiple-access (SS-MC-MA) waveform for high data rate UWB applications, taking into consideration the European UWB context. This new UWB scheme respects the parameters of the multiband orthogonal frequency division multiplexing (MB-OFDM) technique which is one of the candidates for wireless personal area networks (WPAN) standardization. We optimize the spreading code length and the number of codes in our proposed scheme in order to maximize the system range for a given target throughput. Furthermore, we dynamically distribute the time-frequency codes that provide frequency hopping between users in order to improve our system range. We show that our adaptive system transmits information at much higher attenuation levels and with larger throughput than the ones of the MB-OFDM proposal. Hence, we conclude that our proposed system can be advantageously exploited for UWB applications.

Key words: Multi-carrier spread-spectrum, resource allocation, UWB.

1. Introduction

Ultra-wideband (UWB) has emerged as an exciting technology for short range, high data rate wireless communications since 2002 when the Federal Communications Commission (FCC) agreed on the allocation of a 3.1–10.6 GHz spectrum for unlicensed use of UWB devices [1]. The FCC imposed a power spectral density (PSD) limit of -41.25 dBm/MHz in order to reduce interference with existing spectrum allocations.

One of the main multiple-access techniques considered by the IEEE 802.15.3a standardization group is a multiband orthogonal frequency division multiplexing (MB-OFDM) supported by the Multiband OFDM Alliance (MBOA) [2], [3]. In this paper, we propose a new UWB waveform based on a spread spectrum multi-carrier multiple-access (SS-MC-MA) scheme while respecting the OFDM parameters of the MBOA solution and taking into consideration the European UWB context. Then, we optimize the spreading code length and the number of codes of the proposed scheme in order to maximize the system range. These optimizations do not take into account the channel coding scheme. Furthermore, we propose an allocation algorithm that maximizes the system range by dynamically distributing the time-frequency codes that provide frequency hopping between users.

This paper is organized as follows. Section 2 presents briefly the multiband OFDM solution, followed by a description of our proposed SS-MC-MA scheme. Section 3 studies the SS-MC-MA system optimization for range maximization. Section 4 describes the dynamic TFC algorithm applied to the SS-MC-MA scheme. Simulation results showing the interest of the proposed adaptive scheme in UWB applications are given in Section 5, followed by the conclusion in Section 6.

2. System model

2.1 Multiband OFDM in the European context

The MBOA solution is based on the combination of an OFDM modulation with a multibanding approach, which divides the 7.5 GHz UWB spectrum into 14 sub-bands of 528 MHz each. The OFDM scheme consists of 128 subcarriers, out of which 100 are assigned to data tones. The modulation used is a quadrature phase-shift keying (QPSK), which leads to the transmission of 200 bits per OFDM symbol. The MBOA solution offers potential advantages for UWB applications, e.g., the signal robustness against channel selectivity and the efficient exploitation of the energy of every signal received within the prefix margin.

Initially, most of the studies have been performed on the first 3 sub-bands (3.1–4.8 GHz). The FCC PSD limit of -41.3 dBm/MHz was imposed on the whole 14 sub-bands, whereas with the European Electronic Communications Committee (ECC) regulations of March 2006 much lower PSD limits were imposed on the UWB spectrum, except on the 6–8.5 GHz range where a similar -41.3 dBm/MHz limit was considered [4]. Hence, we perform our studies on sub-bands 7, 8 and 9 (6.33–7.92 GHz) of the MBOA solution.

2.2 Proposed SS-MC-MA scheme

To improve the system performance, we propose a SS-MC-MA scheme which consists in assigning to each user a specific block of subcarriers [5]. This scheme is applied to UWB while respecting the OFDM parameters of the MBOA solution [6]. The spreading is in the frequency domain in order to improve the signal robustness against the frequency selectivity of the UWB channel and against narrowband interference. If we consider 3 users transmitting simultaneously, at a given time each user is allocated a group of 100 subcarriers equivalent to one of the 3 sub-bands (7, 8 and 9) of 528 MHz bandwidth. Each sub-band can be divided into several blocks, each of them including a number of subcarriers equal to the spreading code length. In addition, the only modulation used is the QPSK as with the MBOA solution.

2.3 Channel model

The channel model used for our study is the one adopted by the IEEE 802.15.3a committee for the evaluation of UWB physical layer proposals [7]. It is a modified version of the Saleh-Valenzuela model for indoor channels, fitting the properties of measured UWB channels. A lognormal distribution is used for the multipath gain magnitude. In addition, independent fading is assumed for each cluster and each ray within the cluster. Moreover, four different channel models (CM1 to CM4) are defined for the UWB system modeling, each with arrival rates and decay factors chosen to match different usage scenarios and to fit line-of-sight (LOS) and non-line-of-sight (NLOS) cases.

3. SS-MC-MA system optimization

The SS-MC-MA system optimization is divided into 2 steps. First, we will find the optimal number of blocks that maximizes the system margin for a target throughput, and then we will optimize the code length and the number of codes in order to maximize the system range with lower variable throughput.

The throughput of an OFDM system in bits per symbol is derived from Shannon theorem by

$$R_{OFDM} = \sum_{k \in S} \log_2 \left(1 + \frac{1}{\Gamma} \left| h_k \right|^2 \frac{E_k}{N_0} \right), \tag{1}$$

where S is the group of used subcarriers, Γ the signal-to-noise ratio gap (normalized SNR), h_k and E_k the frequency-domain response and the transmitted power density of the k^{th} subcarrier respectively, and N_0 the noise density. The total throughput in bits per symbol of a SS-MC-MA system using a zero-forcing detection is given by [8]

$$R_{SS-MC-MA} = \sum_{b=1}^{B} R_b = \sum_{b=1}^{B}\sum_{c=1}^{C_b} R_{c,b} = \sum_{b=1}^{B}\sum_{c=1}^{C_b} \log_2\left(1 + \frac{1}{\Gamma}\frac{L_b^2}{\sum_{i=1}^{L_b}\frac{1}{|h_{i,b}|^2}}\frac{E_{c,b}}{N_0}\right), \quad (2)$$

where B is the number of blocks, C_b the number of codes used for block b, L_b the code length of block b, $E_{c,b}$ the power allocated to code c of block b, with the constraint

$$\sum_{c=1}^{C_b} E_{c,b} \le E, \quad \forall b. \quad (3)$$

Using the Lagrange multipliers in (2) and (3), we find that the optimal solution which maximizes the system throughput would be to have $E_{c,b} = E / C_b$ and $C_b = L_b, \forall b$. Moreover, in the UWB context, the modulations used are limited to a QPSK. Thus, the UWB throughput in bits per symbol becomes

$$R_{UWB} = 2\sum_{b=1}^{B} L_b \le \sum_{b=1}^{B} L_b \log_2\left(1 + \frac{1}{\Gamma}\frac{L_b}{\sum_{i=1}^{L_b}\frac{1}{|h_{i,b}|^2}}\frac{E}{N_0}\right). \quad (4)$$

Property 1: The throughput R_{UWB} is only reachable if the expected value

$$\mathrm{E}\left[\frac{1}{|\hat{h}_{i,b}|^2}\right] \le \frac{1}{3}, \quad (5)$$

with $|\hat{h}_{i,b}|^2 = |h_{i,b}|^2 \, E / \Gamma N_0$.

Proof: From (4) we can write

$$\sum_{b=1}^{B}\sum_{i=1}^{L_b}\frac{1}{|\hat{h}_{i,b}|^2} \le \sum_{b=1}^{B}\frac{L_b}{3}. \quad (6)$$

If n is the total number of used subcarriers, then $\sum_b L_b = n$ and (6) becomes

$$\frac{1}{n}\sum_{b=1}^{B}\sum_{i=1}^{L_b}\frac{1}{|\hat{h}_{i,b}|^2} \le \frac{1}{3}. \tag{7}$$

■

3.1 Optimization of the number of blocks

In this study, we want to find the optimal number of blocks B that maximizes the SS-MC-MA system margin with a fixed modulation and a fixed target throughput (200 bit/symbol). Let γ_b be this margin per block. From (4), we can write

$$R_{UWB} = 2n = 2\sum_{b=1}^{B} L_b = \sum_{b=1}^{B} L_b \log_2\left(1+\frac{1}{\gamma_b}\frac{L_b}{\sum_{i=1}^{L_b}\left(1/|\hat{h}_{i,b}|^2\right)}\right) \tag{8}$$

and

$$\gamma_b = \frac{1}{3}\frac{L_b}{\sum_{i=1}^{L_b}\left(1/|\hat{h}_{i,b}|^2\right)}. \tag{9}$$

Theorem 1: To maximize the noise margin of the SS-MC-MA system, and consequently the system range, a code length equal to the number of useful subcarriers should be used, i.e. one single SS-MC-MA block should be used.

Proof: We want to maximize the minimum value of γ_b.

Let
$$\sum_{i=1}^{L_b}\frac{1}{|\hat{h}_{i,b}|^2} = \frac{L_b}{n}\sum_{b=1}^{B}\sum_{i=1}^{L_b}\frac{1}{|\hat{h}_{i,b}|^2} + \alpha_b = \frac{L_b}{n}\alpha + \alpha_b,$$

then
$$\gamma_b = \frac{1}{3}\frac{L_b}{\frac{L_b}{n}\alpha + \alpha_b}.$$

We have
$$\alpha = \sum_{b=1}^{B}\sum_{i=1}^{L_b}\frac{1}{|\hat{h}_{i,b}|^2} = \sum_{b=1}^{B}\left(\frac{L_b}{n}\alpha + \alpha_b\right) = \alpha + \sum_{b=1}^{B}\alpha_b.$$

Thus, we find that
$$\sum_{b=1}^{B}\alpha_b = 0.$$

Let γ be the noise margin of the SS-MC-MA system with one block, and let b' be such that $\gamma_{b'} > \gamma$, then $\alpha_{b'} < 0$. Hence, $\exists b''$ such that $\alpha_{b''} > 0$, i.e. $\gamma_{b''} < \gamma$, and $\min_b \gamma_b < \gamma$.

Thus, $L = n$ maximizes the margin, i.e. the optimal choice for a given throughput is to use a spreading code length equal to the total number of useful subcarriers which is equal to 100 in the UWB context. ■

Consequently, it is not necessary to know the channel coefficients at the transmitter side to distribute the subcarriers between the blocks, since all these subcarriers are used within the same single block. Furthermore, this theorem shows that the SS-MC-MA noise margin can never be lower than the OFDM noise margin. This is due to the energy gathering capability of SS-MC-MA which can exploit, contrarily to OFDM, the residual energy conveyed by each subcarrier. The SS-MC-MA system range is therefore larger than the OFDM system range.

3.2 Range improvement with variable throughput

Now, we optimize the code length L and the number of codes N in order to maximize the system range when the UWB throughput of 200 bit/symbol is not reachable at high attenuation levels.

In a general approach with variable throughput, the number of codes N can be lower than the code length L and *Theorem 1* is not applicable anymore. In this case, a multiple blocks configuration has to be considered and each block can exploits its own code length L_b. But finding the optimal block sizes amounts to resolving a complex combinational optimization problem that can not be reduced to an equivalent convex problem. Then, no analytical solution exists and optimal solution can only be obtained following exhaustive search [8]. In order to avoid prohibitive computations, we assume a single block configuration system.

Maximizing the system range is equivalent to maximizing the system throughput. The optimal non-integer throughput for the single block system is given by

$$R = L \log_2 \left(1 + \frac{L}{\sum_{i=1}^{L} \left(1 / |\hat{h}_i|^2 \right)} \right). \tag{10}$$

Theorem 2: With a QPSK modulation and a PSD constraint of $\sum_{c=1}^{L} E_c \leq E$, the optimal number of codes that can be used for a given spreading code length L is $N = \left\lfloor L\left(2^{R/L} - 1\right)/3 \right\rfloor$, with R given by (10).

Proof: With the optimal number of codes *N*, the PSD constraint should be respected, whereas with $N+1$ codes, it shouldn't. Hence, *N* should satisfy the following 2 conditions

$$\begin{cases} E - \sum_{c=1}^{N} E_c = \frac{L}{\alpha}\left(2^{R/L} - 1\right) - \frac{N}{\alpha}\left(2^2 - 1\right) \geq 0, \\ E - \sum_{c=1}^{N+1} E_c = \frac{L}{\alpha}\left(2^{R/L} - 1\right) - \frac{N+1}{\alpha}\left(2^2 - 1\right) < 0, \end{cases} \tag{11}$$

with $$\alpha = L^2 / \sum_{i=1}^{L} \frac{N_0 \Gamma}{|h_i|^2}.$$

From (11), $N \leq L\left(2^{R/L} - 1\right)/3$ and $N > L\left(2^{R/L} - 1\right)/3 - 1$. Hence, $N = \left\lfloor L\left(2^{R/L} - 1\right)/3 \right\rfloor$. ■

From (10) and *Theorem 2*, since the number of codes cannot be larger than the code length, the maximum reachable throughput for a given *L* becomes

$$R(L) = 2 \times \min\left\{ \left\lfloor \frac{L}{3}\left(2^{R/L} - 1\right) \right\rfloor, L \right\} = 2 \times \min\left\{ \left\lfloor \frac{L^2}{3\sum_{i=1}^{L}\left(1/|\hat{h}_i|^2\right)} \right\rfloor, L \right\}. \tag{12}$$

Finally, the maximum reachable throughput with the optimal code length becomes

$$R_{\max} = \max_{1 \leq L \leq N} \{R(L)\}. \tag{13}$$

4. Time-frequency codes exploitation

In the MBOA solution, unique logical channels corresponding to different piconets are defined by using different time-frequency codes (TFC) for each sub-band group. These codes provide frequency hopping from a sub-band to another at the end of each OFDM symbol. The configuration proposed by the MBOA solution consists in choosing the TFC regularly without taking into consideration the channel response state of each user for each sub-band. In our study, we use a dynamic TFC (DTFC) distribution, different from the distribution of the MBOA solution, in order to maximize the SS-MC-MA system range.

We consider 3 users, and consequently 3 TFC codes, distributed on sub-bands 7, 8 and 9 of the MBOA solution. Over a given period *T* equivalent to the duration of an OFDM symbol, each user occupies one of the 3 available sub-bands. To find the number of unique possible distributions of the TFC over 3 successive periods *T*, we consider a combinational problem: over one period, we have a permutation with order and without repetition of 3 users on 3 sub-bands. Moreover, within each sub-band, the users' order in time is not taken into consideration. We find that the number of unique permutations is equal to 55. In addition, we have a total of 9 different channel responses in the system, since each user has 3 different channel responses corresponding to 3 sub-bands.

5. Simulation results

In this section, we present the simulations performed on sub-bands 7, 8 and 9 of the MBOA solution using the proposed SS-MC-MA scheme and taking into consideration the European context.

Fig. 1 represents the total throughput per OFDM symbol of a single user over CM1 channel model for different channel attenuation levels, before applying the dynamic TFC algorithm. With the MBOA solution, the total throughput of 200 bit/symbol is not reachable at attenuation levels higher than 38 dB, whereas with the proposed SS-MC-MA scheme using a single block of length $L = 100$, we are able to transmit 200 bit/symbol at an attenuation level of 53 dB (15 dB larger range). Moreover, when we optimize the code length *L* and the number of codes *N* of the SS-MC-MA system, we are able to transmit data at much higher attenuations (81 dB), and the reachable range and throughput with adaptive SS-MC-MA are always larger than the ones of an adaptive OFDM system. The number of QPSK modulated subcarriers can vary from 100 to 0 with the called adaptive OFDM scheme, whereas with the MBOA solution the number of active subcarriers is always equal to 100. The optimal values of *L* and *N* that maximize the range of the adaptive SS-MC-MA system for different attenuation levels are given in Fig. 2. We can notice that at high attenuations, *N* is lower than *L*.

Fig. 3 and Fig. 4 represent the total system throughput per 3 OFDM symbols for 3 users over CM1 channel model. In Fig. 3, with the MBOA system using the TFC defined by the solution, the 3 users are able to transmit ($3 \times 3 \times 200 = 1800$ bit/3×symbol) at attenuation levels lower than 41 dB. At attenuation levels from 41 to 43 dB, only 2 users are able to transmit (1200 bit/3×symbol), at levels from 44 to 49 dB only 1 user is able to transmit, and at levels higher than 49 dB no one is able to transmit. When applying the

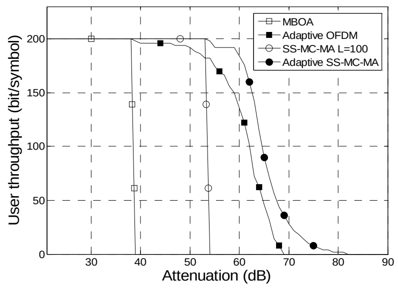

Figure 1. Total throughput of a single user system.

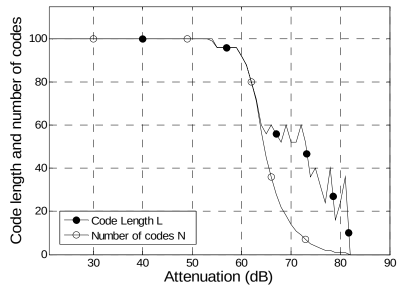

Figure 2. Optimal adaptive SS-MC-MA configuration.

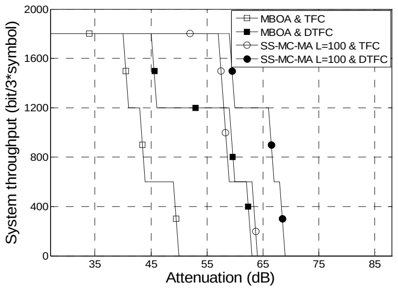

Figure 3. Total throughput of a 3-users system without adaptive schemes.

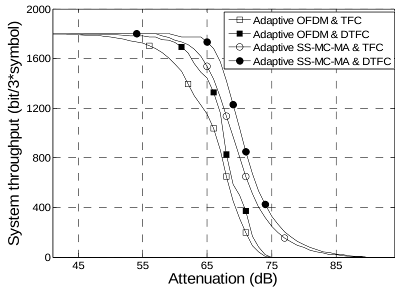

Figure 4. Total throughput of a 3-users system with adaptive schemes.

dynamic TFC (DTFC) algorithm to the MBOA system, the system range increases more than 5 dB, and when applying it to the SS-MC-MA scheme, the system range becomes around 20 dB larger than the MBOA system range. In Fig. 4, the same TFC algorithm is applied to the adaptive OFDM system and to the optimized SS-MC-MA system with variable code length *L* and variable number of codes *N*. We notice that the adaptive SS-MC-MA system is able to reach an 89 dB attenuation level. Moreover, with the DTFC applied to the SS-MC-MA system, the reachable range becomes larger, and for a given attenuation level, the throughput is improved. Similar results are obtained with CM2, CM3 and CM4 channel models.

6. Conclusion

In this paper, we proposed a SS-MC-MA waveform which is new for high data rate UWB applications and which respects the OFDM parameters of the MBOA solution, taking into account to the European UWB context.

Then, we optimized the spreading code length and the number of codes in order to maximize the system range. Furthermore, we proposed an allocation algorithm which maximizes the system range by distributing the time-frequency codes dynamically, contrarily to the MBOA solution where the time-frequency codes are distributed regularly without taking into consideration the channel response of each user for each sub-band. We showed that the SS-MC-MA system is able to transmit information at attenuation levels much higher than the attenuation limits of the OFDM solution. These optimizations did not take into account the channel coding scheme. However, the performance comparison of the final systems with channel coding shows that our proposed adaptive SS-MC-MA scheme and proposed TFC algorithm can be advantageously exploited for high data rate UWB applications. These improvements can be obtained without changing the radio-frequency front-end compared to the MBOA solution.

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