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SYMBOL SPREADING FOR ULTRAWIDEBAND SYSTEMS BASED ON MULTIBAND OFDM

Iyappan Ramachandran[1,2], Yves-Paul Nakache[1], Philip Orlik[1], Andreas F. Molisch[1,3], Jinyun Zhang[1]

[1] Mitsubishi Electric Research Labs, 201 Broadway, Cambridge, MA 02139, USA,
{nakachey, porlik, molisch, jzhang}@merl.com
[2] Author for correspondence. Now at the Dept. of EE, Univ. of Washington, Seattle, WA 98105, USA,
iyappan@ee.washington.edu, Fax: +1 206 543 3842
[3] also at the Department of Electroscience, Lund University, Sweden

Abstract - We investigate the effect of symbol spreading on the performance of ultrawideband systems based on multiband OFDM. Ultrawideband channels offer the possibility of very high frequency diversity, as the used bandwidth is much larger than the coherence bandwidth of the channel. In multiband-OFDM, frequency diversity stems from (i) forward error correction coding, which distributes the symbols associated with one bit among different tones, and (ii) interleaving, which distributes the symbols among different employed frequency bands. We show that for weak (rate 3/4) error correcting codes, the achieved diversity order is insufficient. However, the use of Walsh-Hadamard spreading gives additional diversity within each frequency band and greatly improves the performance. Furthermore, we propose a novel scheme for grouping OFDM tones before the spreading is performed. This grouping gives additional flexibility in the system design.

Keywords - ultrawideband, multicarrier-CDMA, frequency diversity, multiband-OFDM

I. INTRODUCTION

For the last decade, ultrawideband (UWB) communications has attracted great interest from the academic and military research communities. In UWB systems, the available information is spread over a very large bandwidth, leading to a low spectral density, and thus low interference to and from other existing services. Due to this reason, the Federal Communications Commission (FCC) of the USA issued in February 2002 a first report and order allowing limited *unlicensed* operation of ultrawideband devices [1]. This triggered a flood of research and development activities in the industrial community, and the IEEE established a standardization body, called IEEE 802.15.3a, for developing a physical-layer standard for high-data-rate communications based on ultrawideband. The goal of this standard is to achieve data rates of 110Mbit/s at 10m distance, 200 Mbit/s at 4m distance, and 480Mbit/s at shorter distances.

Following the pioneering work of Win and Scholtz [2], [3], [4], ultrawideband communications was mainly associated with time-hopping impulse radio (TH-IR). While this approach seems to be the best method for low-data-rate communications (due to performance considerations [5] as well as implementation simplicity), it will not be used for high-data rate communications of the IEEE standard. Rather, a MB-OFDM (multiband orthogonal frequency division multiplexing) approach [6] has been proposed as a possible choice. In this method, the available frequency spectrum is divided into several bands of 528MHz width each. Only one such band is used at a time; the used band is changed every 300ns. During each 300ns interval, one OFDM symbol is transmitted.

One of the main advantages of UWB transmission is the large amount of available frequency diversity. For impulse radio, it can be exploited by appropriate Rake receivers [7], [8], [9]. However, it is well known that *uncoded* OFDM does not provide any frequency diversity - as a matter of fact, it is one of the underlying principles of OFDM to convert a frequency-selective channel into several parallel flat-fading channels. While frequency diversity is not required to achieve optimum (Shannon) capacity, several other restrictions in the standard make it desirable to have frequency diversity available. The current IEEE standards proposal thus foresees three measures to achieve this purpose:

- for the 110 and 200Mbit/s mode, repetition frequency diversity is introduced.
- in all modes, convolutional coding coding is used. Appropriate *coding* recovers a large part of the possible diversity [10], as it distributes the symbols associated with a certain information bit among different OFDM tones.
- an interleaver distributes (coded) symbols belonging to a certain information bit among different frequency bands

While those measures go a long way to recovering frequency diversity, they are not sufficient under all circumstances. Especially for the 480 Mbit/s mode, a significant performance loss can be observed [6]. In this paper, we suggest a way to circumvent this problem, by spreading the OFDM symbols among different tones, using the principles of multicarrier-OFDM [11], [12]. Our main contributions are thus the following:

- we analyze the frequency diversity degree of the different data rates of the multiband-OFDM proposal, in the standardized UWB channel models [13]
- we show that the introduction of symbol spreading leads to dramatic performance gains for the 480Mbit/s mode, but not for the 110 and 200 Mbit/s modes, and give physical explanations of that fact
- we introduce a novel scheme for spreading only in a

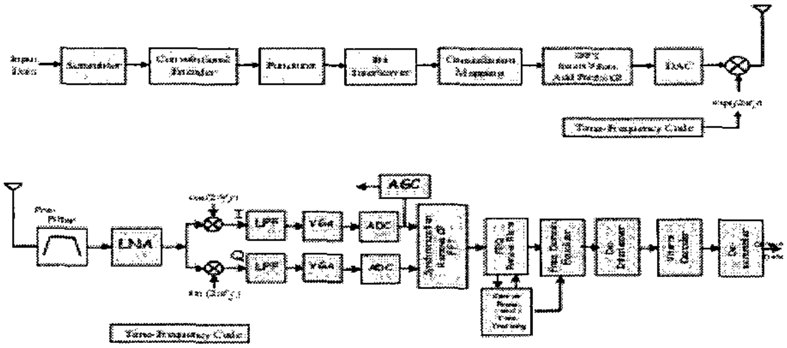

Fig. 1
Blockdiagram of MB-OFDM system

subset of frequencies, which has advantages both with respect to design flexibility and performance.

The remainder of the paper is organized the following way: Section II describes the multiband-OFDM system we analyze. Section III introduces the symbol spreading, and analyzes the performance of the unspread and the spread system in different channels. Next, we discuss the specific properties of the multiband-OFDM system that make the "conventional" MC-CDMA system less suitable, and introduce as a remedy the spreading of symbols within a subgroup of tones. A summary and conclusions wrap up the paper.

II. SYSTEM DESCRIPTION

For our analysis, we consider the system currently considered by the IEEE standardization [6], as depicted in Fig. 1. The source data, which have a rate of 110Mbit/s, 200Mbit/s, or 480Mbits/s, are first scrambled, and then sent through a $1/3$ convolutional encoder using code polynomials $[133]_8$, $[145]_8$ and $[175]_8$. The code is then punctured to result in code rates $11/32$, $5/8$ and $3/4$ for the three data rates respectively. The coded bits are then interleaved with an interleaver length of 600 bits. This makes sure that different coded bits belonging to the same source bit are transmitted in different frequency subbands. The interleaved bits are then mapped onto QPSK symbols. A block of 100 QPSK symbols is then serial-to-parallel converted, and can then be interpreted as tones in the frequency domain. Pilot tones (for the tracking of the carrier phase) and null tones (for a gentle spectral rolloff) are added, to make a total of 128 tones. These are then subjected to an IFFT (inverse fast Fourier transform), and a 60ns cyclic prefix or zero padding is added (At the time of writing this paper, the question of using cyclic prefix or zero suffix in the standard is still being discussed. In our simulations however, we use cyclic prefix). The resulting time-domain (serial) signal is upconverted with a local oscillator whose frequency changes for each transmitted OFDM symbol (about 300ns), according to a time-frequency code. In the "baseline" mode, only three center frequencies are used, namely 3432MHz, 3960MHz and 4488MHz. Optional modes will use a larger set of possible center frequencies; however, all our simulations are done for the 3-frequency case.

The signal is then sent through a multipath channel that distorts the signal and adds white Gaussian noise (as well as possible interference). We use a modified Saleh-Valenzuela model [14] with lognormally-fading amplitudes that was standardized by the IEEE [13]. The standardized model actually prescribes 100 channel realizations, giving the amplitude, polarity, and delay of each multipath component. These realizations form the basis for our simulations. The model specifies 4 different environments: CM1: (line-of-sight, distance between transmitter and receiver less than $4m$), CM2: (NLOS, distance TX-RX $< 4m$), CM3 (NLOS, distance TX-RX $4 - 10m$), CM4 (heavy multipath). The rms delay spreads in those environments vary between 5ns (CM1) and 25ns (CM4). In order to better work out the essential points related to frequency selectivity, we will not include shadowing in our simulations.

In the receiver, the process is essentially reversed. The received signal is first filtered, amplified with a low-noise amplifier, and downconverted (with the time-frequency code), low-pass filtered, amplified (with a variable gain amplifier whose amplification is determined by the automatic gain control loop), and analog-to-digital converted. The digital signal is then subjected to an FFT, the cyclic prefix is stripped off, and a one-tap equalization is performed. and the pilot tones are extracted to allow a fine tuning of the local oscillators. The data are de-interleaved, and decoded with a Viterbi encoder with traceback length 49. This length is sufficient, which we verified by trying larger traceback lengths without difference in the performance curves.

The data are transmitted in packets with 1 KByte of user data each. The performance goal is a packet error rate of 8%, corresponding to a bit error probability (BER) of 10^{-5}. At the beginning of each packet, a preamble is transmitted that contains, among other things, channel estimation symbols. For all subsequent considerations, we will assume ideal channel estimation (for a discussion of this assumption, see [15]).

III. Symbol spreading

A. Basic principle

As mentioned in the introduction, pure OFDM does not contain any frequency diversity. In the case that capacity-achieving codes are used, this is not a drawback: OFDM has been shown to achieve capacity [16]. However, in the case of multiband-OFDM, the modulation format is restricted to QPSK. Furthermore, interleaving over different temporal states is not possible: the packet duration (on the order of $100\mu s$) is much smaller than the channel coherence time (on the order of 10ms). Thus frequency diversity is essential for achieving good performance.

The multiband-OFDM scheme has a certain amount of inherent frequency diversity. On one hand, the convolutional code spreads the symbols belonging to one information bit both between different 500MHz bands and between tones within a subband. This effect is pronounced in the 110Mbit/s mode, where a code rate of $11/32$ is used. It is less explicit in the 200Mbit/s and 480Mbit/s mode, where the code rates are $5/8$ and $3/4$, respectively. In addition, in both the 110 and 200 Mbit/s modes, symbols are repeated in two subsequent OFDM symbols (and thus, in different subbands); this leads to an extra frequency diversity order 2.

We confirmed these qualitative considerations by simulations of the complete system. Figure 2 shows the performance in the CM4 channel model, as well as in AWGN. We see that the performance for the 110Mbit/s mode, and for the 200Mbit/s mode is good. The slope of the BER-vs-SNR curve is similar to the AWGN curve. This indicates that the diversity order of the system is sufficient in those cases. However, for the 480Mbit/s mode, the diversity achieved is not sufficient - the slope of the BER curve in CM4 is much flatter than in AWGN. This stems from the fact that the only diversity is created by the error correction code, which itself is high rate and thus has little diversity.

A remedy for this problem, which is well known from "conventional" wireless systems, is multicarrier-CDMA [12], [11], [17]. In this system, the symbols are multiplied with a Walsh-Hadamard matrix before feeding to the IFFT, thereby spreading each symbol over the entire transmission bandwidth and achieving a high degree of frequency diversity. As all the used Walsh-Hadamard codes are orthogonal, they can be transmitted in parallel; the total data rate is thus unchanged. Walsh-Hadamard codes can thus also be seen as codes with code rate 1. At the receiver, the output of the FFT is multiplied by the W-H matrix as a despreading operation. Note that the orthogonality is destroyed in a frequency-selective channel, but would be recovered by a (one-tap) zero-forcing equalizer in the OFDM receiver as long as the cyclic prefix is sufficiently long.

The drawback of MC-CDMA systems is the inherent noise enhancement. The one-tap equalizer multiplies the signals on weak tones with larger coefficients, which also amplifies the noise on these tones. In the despreader, the noise is distributed among all tones. Thus, the SNR of the "good" tones is lowered. It is thus essential to use a MMSE equalizer, and not a zero-forcing equalizer even though it cannot completely recover the orthogonality. In our simulations, we use a MMSE equalizer for both the spread and the unspread schemes. Figure 3 shows the performance of a *generic* multiband-OFDM system (which does not have pilot tones or null tones, and all 128 tones are data tones). We see that spreading can lead to a performance improvement of more than 3dB in CM1 (at a BER of 10^{-5}), and much more in CM4. We can also observe the (well-known) cross-over behavior: due to noise enhancement, unspread OFDM is better at very high BERs, though the difference is minuscule.

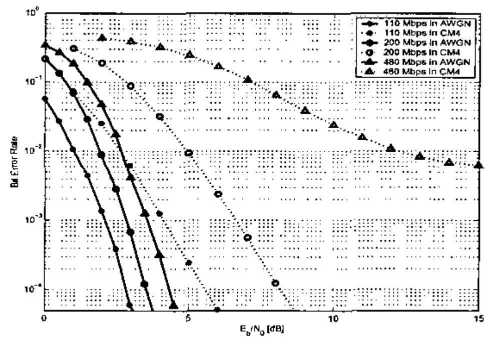

Fig. 2
BER of coded UWB OFDM system in AWGN channels (solid lines) and strong multipath channel CM4 (dashed).

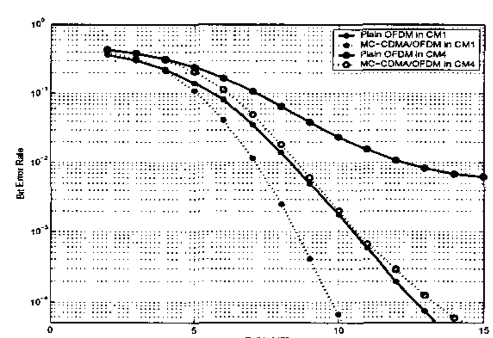

Fig. 3
BER for plain OFDM (solid) and MC-CDMA (dashed) in channel models CM1 and CM4.

We also find that for such a generic OFDM system, spreading over as many tones as possible is always beneficial. Figure 4 shows the BER as a function of the number of tones over which each QPSK symbol is spread, and thus the diversity order. We find the (not surprising) result that most of the reduction in BER can be achieved with a relatively small amount of diversity, namely spreading over 8 tones.

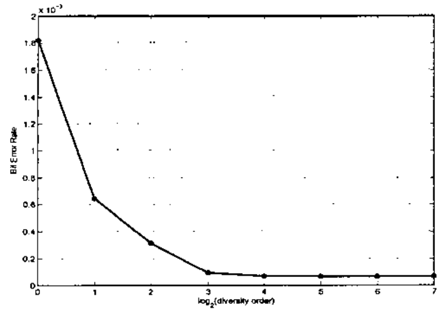

Fig. 4
BER as a function of the number of tones over which the signal is spread.

B. Frequency grouping

In the above we have proven that the MC-CDMA scheme (which up to now has been studied only in "standard" narrowband wireless channels) is also useful in UWB channels with their different fading statistics, and works well in conjunction with the time-frequency interleaving scheme used by the multiband-OFDM scheme. However, this is not completely surprising. What makes the problem challenging are some additional restrictions imposed by the system specifications of the MB-OFDM scheme:

- there are 12 pilot tones that are interspersed between the data-carrying tones. These pilot tones should not be spread, because they are used both for phase tracking, and for channel re-estimation [15]. Residual errors from imperfect despreading (especially in the context of imperfect channel estimation) is highly undesirable.
- null tones are added for the purpose of spectral shaping. These tones show poor SNR because less power is assigned to them. Furthermore, no channel estimate is available for these tones, so that even the one-tap equalizer cannot work on them.

It follows that not all tones should be spread. Rather, the pilot tones and null tones should be excluded from the spreading process. However, the most efficient (recursive) Walsh-Hadamard spreaders exist for the case that the number of spread tones N_s is a power of 2.

All these problems can be solved by the spreading scheme sketched in Fig. 5. The OFDM tones carrying data symbols are first arranged into several groups, each of which has size 2^M, and each group is then spread with a Walsh-Hadamard matrix of this size; as the groups are mutually orthogonal, the same Walsh codes can be used in each of the group.

The pilot tones and null tones are not included in any of the groups that are spread; this solves the problem of noise enhancement and "contamination" of the pilot tones. The total of 100 data tones can be made up from groups of size

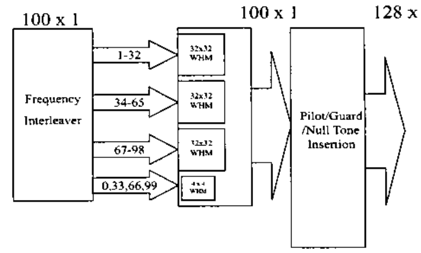

Fig. 5
Grouping of frequencies for spreading.

2^M, so that the efficient WH-spreaders can be used. Finally, taking a smaller group size means that the number of possible input levels is restricted, which alleviates any problems caused by low-resolution analog-to-digital converters.

In the following, we consider two different types of grouping

1) Block grouping: in this approach, a group of $L = 2^M \geq R$ adjacent tones is taken as one group, over which the symbols are spread. Here, R is the ratio of the bandwidth (500MHz) to the coherence bandwidth B_c of the channel
2) Interleaved grouping: in this scheme, the first group of tones uses $1, 1+K, 1+2K, ...$the second one uses the tones $2, 2+K$, $2+2K, ...$, and so on, see Fig. 6. A somewhat related scheme was proposed by one of us in a different context (space-frequency codes) [18].

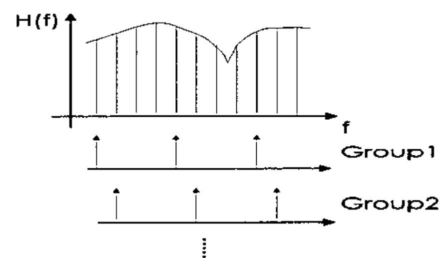

Fig. 6
Interleaved grouping of tones.

The disadvantage of the group-spreading is the fact that the achievable diversity is smaller. However, this is not a serious restriction in practice, for two reasons:

1) if the delay spread is large (large amount of frequency diversity), each group can achieve a diversity order that is equal to the number of tones within each group. Thus, a group consisting of four tones achieves fourth-order diversity. At a target BER of 10^{-5}, the SNR gain of fourth-order to, e.g., 16- or even 128-order diversity is very small.
2) if the delay spread is small, the achievable diversity order is given by R. This diversity can be almost opti-

mally be exploited by using the interleaved scheme, with $KF_t \geq B_c$, where F_t is the tone spacing (frequency difference between two adjacent tones).

C. Simulation results

In this subsection, we study the performance of a multiband-OFDM scheme according to the standards document [6]. We will find that the presence of the pilot tones and null tones leads to a behavior that is different from that of the generic OFDM system in Sec. III.A.

Figure 7 shows the performance in CM1. We find that spreading the signals over 128 tones gives a performance improvement of more than $2dB$ over the unspread scheme, however, this improvement is noticeably smaller than in the generic OFDM system. The reason for this smaller improvement is the loss of orthogonality due to the spreading of the null tones in the multiband-OFDM scheme, about which no channel information is available. Grouping the 100 data tones as $100 = 3 * 32 + 4$ instead of spreading all the 128 tones improves the performance by about 0.75 dB. We improve by another 0.75 dB by using tone-interleaved grouping.

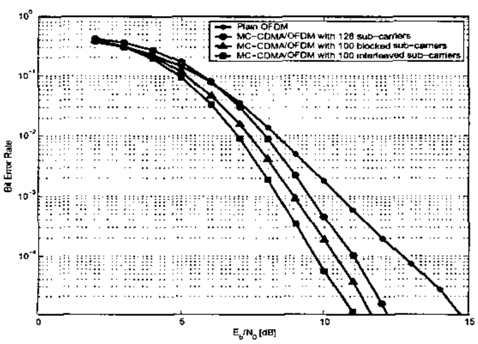

Fig. 7
BER of MBOA scheme in CM1: pure OFDM, MC-CDMA spread over 128 tones, MC-CDMA with block grouping, MC-CDMA with interleaved grouping.

Figure 8 shows a similar plot for the performance in CM4. We find that the advantage of using the grouping is much higher in this case (more than $5dB$), while the difference between the block grouping and the interleaved grouping remains small. However, the interleaved grouping again shows superior performance. The performance loss compared to a generic scheme (without pilot and null tones) is larger in this case (about 3dB at 10^{-5} BER, though it is only about 1dB at 10^{-4}). This results from a loss of diversity order: there is one group with only four tones, so that the maximal diversity order for this is 4. The use of different spreading sequences (e.g., of length 20, so that all groups have the same number of tones) would improve this situation further.

In our analysis and simulations thus far, we have used MMSE equalization for the unspread scheme. In frequency

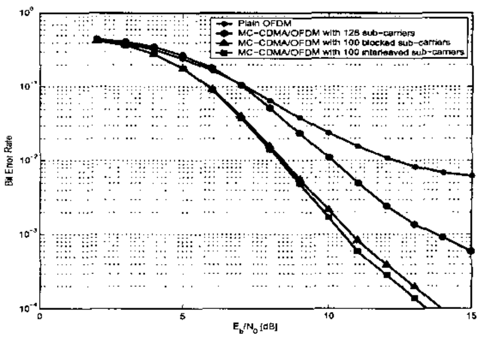

Fig. 8
BER of MBOA scheme in CM4: pure OFDM, MC-CDMA spread over 128 tones, MC-CDMA with block grouping, MC-CDMA with interleaved grouping.

selective channels, the optimum method would be to compute the metrics for soft-decision Viterbi decoding by taking into account the reliability of each sub-carrier. This optimal weighting is accomplished by multiplying each sub-carrier with the conjugate of the complex channel gain at the sub-carrier location, which equalizes only the phase distortion introduced by the channel [19]. Optimal weighting is not applicable in the spread scheme since all the symbols have the same SNR. We compare the performance of the spread scheme with that of the unspread scheme incorporating optimal weighting in CM1 and CM4 channel models in Fig 9. As seen from the figure, the spread scheme still yields more than 1 dB better performance over the unspread scheme incorporating optimal weighting.

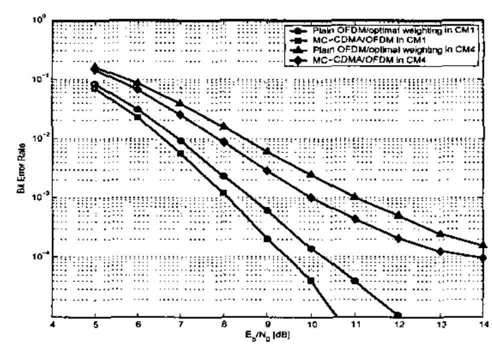

Fig. 9
BER of MBOA scheme: pure OFDM incorporating optimal weighting and MC-CDMA in CM1 and CM4.

Finally, we analyze the impact of low-resolution A/D converters. OFDM in conjunction with a large symbol constellation requires high-resolution A/D converters, in order to avoid significant degradations due to quantization errors. One of the important advantages of the MB-OFDM proposal is the fact that it uses only 4-QAM, which allows the use of low-resolution converters; specifically, for a 5bit ADC, the SNR penalty is less than 1dB. One could argue that the output of the Walsh-Hadamard spreader (and thus the input to the FFT) shows a much larger constellation size than the non-spread scheme, and thus could show higher sensitivity to quantization errors. However, it has to be noted that not all combination of constellation points for the different tones are possible. A better interpretation is to view the concatenation of the spreader and the IFFT as a "modified" IFFT; the input to this modified IFFT is still QPSK. To confirm this interpretation, we performed simulations of a quantized OFDM system as well as a spread system. Results for CM1 are shown in Fig. 10.

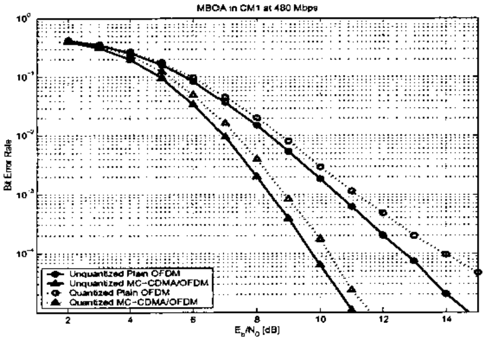

Fig. 10
Effect of quantization on the spreading scheme in CM1.

IV. Summary and Conclusion

We have introduced a new scheme for increasing frequency diversity in multiband-OFDM ultrawideband systems. Combining an appropriate grouping of frequencies with spreading by Walsh-Hadamard codes provides a large amount of frequency diversity. At the same time, the scheme keeps the noise enhancement low, and allows to keep pilot tones as pure sinusoidal oscillations, which provides for better phase tracking. By simulations in the UWB channels standardized by IEEE 802.15.3a, we showed that this scheme has an advantage of at least 1 dB compared to the unspread scheme.

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