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Abstract

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Practical Approaches to Channel Estimation and Interference Suppression for OFDM based UWB Communications

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***Abstract*— *Ultra-wideband* (UWB) communication is a potential technique for future high-speed networks. In this paper, we investigate low complexity signal detection approaches for OFDM based UWB systems. In particular, we develop practical approaches for channel estimation and interference suppression. Computer simulation results show that these techniques can be effectively used in OFDM based UWB systems for performance improvement.**

Key Words: UWB, OFDM, interference suppression, channel estimation.

I. Introduction

Ultra-wideband (UWB) communication has received great attention both by the scientific community and by industry since a “report and order” of the FCC (Federal Communications Commission) allowed limited unlicensed operation of UWB devices in the USA [1]. One of the advantages of UWB is that it can transmit data at a high rate in a short range. This makes it a promising candidate for personal area networks in general, and future home networks in particular. Recognizing this potential, the IEEE has formed a 802.15.3a standardization group, whose task is to establish a physical-layer standard for UWB communications with data rates over 100 Mbit/s [2].

Traditionally, impulse radio has been used for UWB systems with low to moderate data rates [3]. However, within the IEEE 802.15.3a standardization group, *orthogonal frequency-division multiplexing* (OFDM), combined with time-frequency interleaving [4], has emerged as the leading candidate. It is thus of great practical, as well as theoretical, interest to investigate the topics of channel estimation and interference suppression in such a scheme. These aspects have been shown to have a critical impact on the performance of the total scheme. From a theoretical point of view, we note that the 802.15.3a time-frequency interleaved OFDM scheme shows important differences from conventional OFDM as used, e.g., in *asynchronized digital subscribe line* (ADSL) and IEEE 802.11a wireless LANs. New investigations are thus required from a scientific standpoint as well.

The main contributions of this paper are the following: we apply a channel estimation scheme previously proposed by us to exploit the correlations of different tones, and introduce maximum likelihood estimation for the specific diversity scheme used by the OFDM based UWB scheme; and we introduce a new scheme to estimate temporal changes of interference structure for interference suppression.

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II. System Description

Figure 1 shows the block diagram of an OFDM-based UWB system, which closely follows the IEEE 802.15.3a proposal [4]. The binary data stream to be transmitted is first encoded and interleaved (not shown here), and then converted into (complex) QPSK symbols, $\{c_n\}$. To exploit frequency diversity of UWB channels, the symbols are spread by a factor of two within the same OFDM block. Consequently, the symbols for an OFDM block can be expressed as,

$$s_n = \begin{cases} c_n & \text{for } n = 0,\ 1, \cdots, \frac{N}{2}-1, \\ jc_{n-\frac{N}{2}} & \text{for } n = \frac{N}{2},\ \frac{N}{2}+1, \cdots, N-1, \end{cases} \tag{1}$$

where $j = \sqrt{-1}$. Therefore, the corresponding time-domain $OFDM$ signal can be expressed as

$$s(t) = \sum_{k=0}^{N-1} s_n e^{j2\pi f_k t},$$

where $f_k = f_o + k\Delta f$, Δf is the tone space, which relates to the OFDM symbol duration by $T = \frac{1}{\Delta f}$.

This signal is time-frequency interleaved; in other words, the carrier frequency of the local oscillator changes for every transmitted OFDM-symbol (see also Fig. 3). For our simulations, this effect is absorbed into the propagation channels - in other words, the channel is periodically time variant.

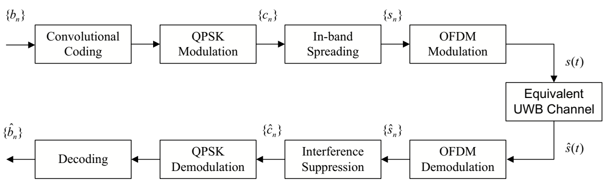

Fig. 1. Block diagram of an OFDM based UWB system.

Due to multipath and interference, the demodulated OFDM signal at the receiver can be expressed as

$$\hat{s}_n = H[n]s_n + i_n + n_n, \tag{2}$$

where $H[n]$ is the frequency response of a UWB channel at the n-th tone for the OFDM symbol under consideration, i_n is interference, and n_n is *additive white Gaussian noise* (AWGN) with zero-mean and variance N_o.

From (1), (2) can be also expressed as

$$\begin{pmatrix} \hat{s}_n \\ \hat{s}_{n+N/2} \end{pmatrix} = \begin{pmatrix} H[n] \\ \jmath H[n+N/2] \end{pmatrix} c_n + \begin{pmatrix} i_n \\ i_{n+N/2} \end{pmatrix} + \begin{pmatrix} n_n \\ n_{n+N/2} \end{pmatrix},$$

or

$$\mathbf{x}_n = \mathbf{H}[n]c_n + \mathbf{i}_n + \mathbf{n}_n, \tag{3}$$

for $n = 0,\ 1, \cdots, N/2-1$, where

$$\mathbf{x}_n = \begin{pmatrix} \hat{s}_n \\ \hat{s}_{n+N/2} \end{pmatrix}, \quad \mathbf{H}[n] = \begin{pmatrix} H[n] \\ \jmath H[n+N/2] \end{pmatrix},$$

$$\mathbf{i}_n = \begin{pmatrix} i_n \\ i_{n+N/2} \end{pmatrix}, \quad \mathbf{n}_n = \begin{pmatrix} n_n \\ n_{n+N/2} \end{pmatrix}.$$

The system uses packet transmission, where each packet contains 8096 (=2^{13}) bits. A rate-1/3 convolutional code with generator sequences 133, 145, and 171 is used. Consequently, the length of each code word is about 24,300 bits. The coded sequence is then converted into 12150 (complex) QPSK symbols. Each OFDM block transmits 50 symbols; therefore, there are 243 OFDM data blocks in each slot. Another 3 OFDM blocks, one for each subbands, are used for training. Each consists of 128 tones, 100 of them are information tones, 12 of them are pilots, and the rest are null tones (transmitting no signal) for *peak-to-average power ratio* (PAPR) reduction.

The above system model describes a fairly generic UWB system based on time-frequency interleaved OFDM. Note that we do not follow all details of the IEEE proposal, as those specs are still being modified by the time of the writing of this submission [4]. However, our model contains all the essential (already fixed) features, so that the relative performance enhancements of our proposed schemes are expected to carry over. In the next sections, we will thus develop approaches for channel estimation and interference suppression.

III. Channel Estimation

In this section, we investigate low complexity channel estimation for OFDM based UWB communications. Channel estimation for OFDM wireless communications has been investigated in [5], [6] and other literature, where high mobility channels are emphasized. However, UWB channels can be regarded as static or quasi-static. Therefore, the channel statistics can be obtained and used to help channel estimation. With the channel's power delay profile, the correlation of channel's frequency response, $r_m = \mathrm{E}\{H[n+m]H^*[n]\}$, can be calculated. Using the correlation matrix, the channel parameters can be estimated by means of *singular value decomposition* (SVD) [6]. It is demonstrated in [5] that with negligible performance degradation, the SVD in channel estimation can be substituted by the *discrete Fourier transform* (DFT) to simplify the estimator. In brief, the channel estimation for OFDM based UWB can be summarized as following:

(i) Calculating raw channel estimation from the training sequence by

$$\tilde{H}[n] = \hat{s}_n s_n^* = H[n] + \tilde{n}_n, \tag{4}$$

where

$$\tilde{n}_n = i_n s_n^* + n_n s_n^*,$$

denotes the effect of interference and noise, and is independent for different n's. In (4), we have assumed that $\mathrm{E}\{|s_n|^2 = 1$, that is, constant modulus modulation.

(ii) Making an *inverse DFT* (I-DFT) to $\{\tilde{H}[n]\}_{n=0}^{N-1}$ using the *fast Fourier transform* (FFT) to obtain $\{\tilde{h}_k\}_{k=0}^{N-1} = \text{I-DFT}\{\tilde{H}[n]\}_{n=0}^{N-1}$.

(iii) Reducing the noise level by exploiting the correlation of channel parameters at different frequencies by

$$\hat{h}_k = \frac{p_k}{p_k + \Delta}\tilde{h}_k,$$

where p_k is determined by channel's power delay profile and

$$\Delta = \frac{1}{N_2 - N_1 + 1} \sum_{k=N_1}^{N_2} |\tilde{h}_k|^2$$

is the estimated interference-plus-noise power.

(iv) Obtaining estimated channel parameters by $\{\hat{H}_n\}_{n=0}^{N-1} = \mathrm{DFT}\{\hat{h}_k\}_{k=0}^{N-1}$.

Figure 2 demonstrates the *mean square-error* (MSE) of the above channel estimation approach. From the figure, we can see that the MSE of the proposed channel estimation approach is much smaller than that of channel noise. Therefore, the impact of channel estimation error on system performance is negligible.

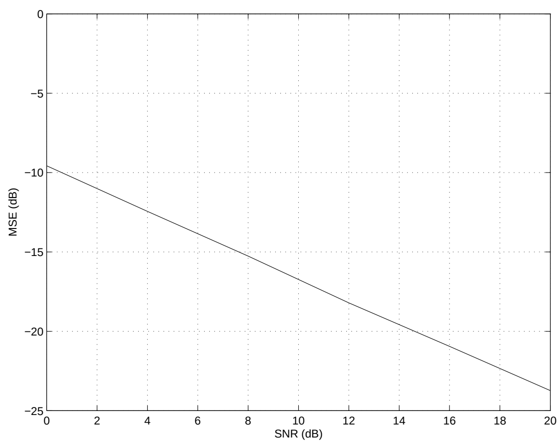

Fig. 2. Channel Estimation Performance.

With the estimated channel parameters, *maximal ratio* (MR) combining can be obtained by

$$\hat{c}_n = \frac{1}{\|\hat{\mathbf{H}}[n]\|} \hat{\mathbf{H}}^H[n]\mathbf{x}_n. \\ \approx \|\hat{\mathbf{H}}[n]\| c_n + \hat{n}_n, \tag{5}$$

where $\hat{n}_n$ denotes the effect of noise that can be expressed as

$$\hat{n}_n = \frac{\hat{H}^*[n]\tilde{n}_n + \hat{H}^*[n+N/2]\tilde{n}_{n+N/2}}{\|\hat{\mathbf{H}}[n]\|}.$$

It can be easily checked that $\hat{n}_n$ is white, Gaussian, and with zero-mean and variance N_o if there is no interference ($i_n = 0$).

The performance of the above MR combining is presented and compared with interference suppression in the next section.

IV. Interference Suppression

The IEEE 802.15.3a system has two types of multiple access: for devices within one piconet, TDMA is used, causing no interference. However, different piconets, which can operate in the same area, differ only by the use of different time-frequency interleaving codes, but do not coordinate the timing of the transmission (uncooperative piconets). Thus, interference is unavoidable. Figure 3 shows time-frequency hopping with interference, where the desired user's hopping pattern is $\{Band-I, Band-II, Band-III\}$ while the interferer user's pattern is $\{Band-I, Band-III, Band-II\}$. From the figure, we can see that, there is always one interference-free band for the desired user and the other two bands are with some interference, depending on timing between interferer and desired users. Let the power ratio of the desired user to interference user be SIR. Due to time-frequency hopping, the power ratio of the desired user and the effective interference (the overlapped area in Figure 3) is reduced to

$$\mathrm{SIR}_e = \frac{1}{3}\mathrm{SIR}, \quad \text{or} \quad \mathrm{SIR}_e \text{ (dB)} = \mathrm{SIR} - 4.8 \text{ (dB)}.$$

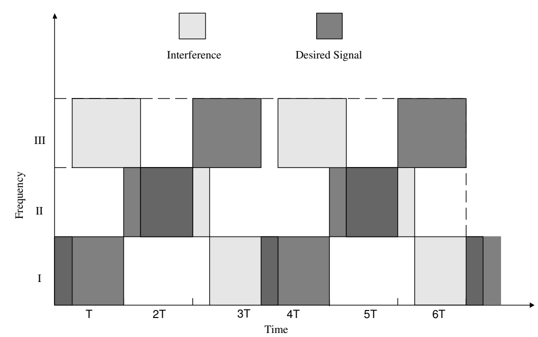

Fig. 3. Time-frequency hopping with interference

Since each symbol is spread to two difference tones, it is possible to further mitigate interference if the interferer user is also using the same spreading scheme. The approach that has been proposed for receive antenna arrays by Winters [7] can be used here for interference suppression. From [7], the optimum coefficient vector that minimizes the MSE of the combiner output, $\hat{c}_n = \mathbf{w}_n^H \mathbf{x}_n$, is determined by

$$\mathbf{w}_n = \mathbf{R}_n^{-1}\mathbf{d}_n, \tag{6}$$

where $\mathbf{R}_n$ and $\mathbf{d}_n$ are defined as

$$\mathbf{R}_n = \mathrm{E}\{\mathbf{x}_n\mathbf{x}_n^H\},$$

and

$$\mathbf{d}_n = \mathrm{E}\{\mathbf{x}_n s_n^*\} = \begin{pmatrix} H[n] \\ \jmath H[n+N/2] \end{pmatrix},$$

respectively. The coefficient vector for MMSE combining can be calculated using (6) with the received signal correlation matrix, $\mathbf{R}_n$.

The estimation of the correlation matrix was investigated in [7] for flat fading channels and in [8] for OFDM with frequency-selective channels. We have tried to apply the approach in [8] for OFDM based UWB systems and found that the estimated correlation matrix is sometimes not positive-definite if each of its element is estimated separately. Therefore, we propose a novel approach for coefficient vector estimation.

Let s_n be a training symbol that is known to the receiver. Then the coefficient vector, $\mathbf{w}_n$ can be found to minimize the following cost function,

$$\mathcal{C}(\mathbf{w}_n) = \frac{1}{\sum_k \lambda^{|n-k|}} \sum_k \lambda^{|n-k|} |\mathbf{w}_n^H \mathbf{x}_k - s_k|^2,$$

where λ is a forgetting factor between 0 and 1. Direct calculation yields that

$$\hat{\mathbf{w}}_n = \hat{\mathbf{R}}_n^{-1} \hat{\mathbf{d}}_n,$$

where

$$\hat{\mathbf{R}}_n = \frac{1}{\sum_k \lambda^{|n-k|}} \sum_k \lambda^{|n-k|} \mathbf{x}_k \mathbf{x}_k^H,$$

and

$$\hat{\mathbf{d}}_n = \frac{1}{\sum_k \lambda^{|n-k|}} \sum_k \lambda^{|n-k|} \mathbf{x}_k s_k^*.$$

With the estimated coefficient vector, the received signals can be combined by

$$\begin{aligned} \hat{c}_n &= \frac{1}{\sqrt{\mathcal{C}(\hat{\mathbf{w}}_n)}} \hat{\mathbf{w}}_n^H \mathbf{x}_n \\ &= \frac{1}{\sqrt{1 - \hat{\mathbf{w}}_n^H \hat{\mathbf{d}}_n}} \hat{\mathbf{w}}_n^H \mathbf{x}_n. \end{aligned} \tag{7}$$

To compare the performance of the MR and the MMSE diversity combiners, we have simulated the whole OFDM based UWB system, according to the system model described in Sec. II. Figure 4 compares performance of the MR and the MMSE combiners, respectively. From the figure, we can see that performance of the MR combiner is better than the MMSE combiner when there is no interference. When there is no interference, the MR and the MMSE combiners should be equivalent if the exact coefficients for diversity combining are used. Since more accurate coefficients for the MR combiner can be estimated, it has better performance than the MMSE combiner. However, when interference appears, the MMSE combiner has very good performance while the MR combiner does not work.

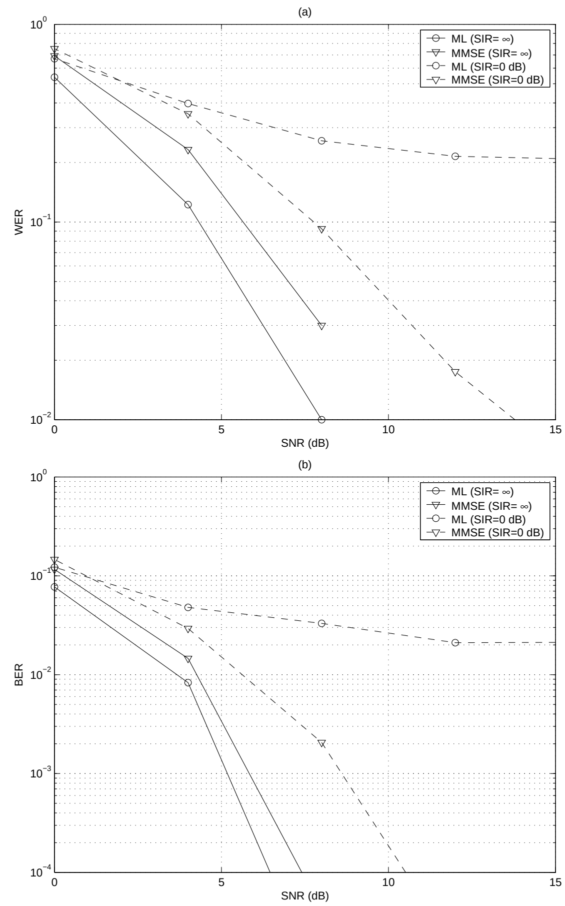

Fig. 4. Performance comparison of ML and MMSE diversity combiner.

V. Random Interference Suppression

In UWB systems, each slot/package contains about a hundred OFDM blocks. As the different piconets (users with different time-frequency codes) are uncoordinated, the interference situation might change during the transmission of a packet. In this case, we need to change the coefficients of the MMSE combiner according to interference environments.

There are 12 pilot tones for each OFDM block in Strawman's proposal [4]. In the current proposal, those pilot tones are located at fixed frequencies. We suggest a new scheme where the pilot tones are rotated through all possible subcarriers. With the new pilot scheme, the coefficients for the MMSE combiner can be adaptively estimated and up-dated according to interference environments.

Figure 5 demonstrates the performance of the MMSE combiners with fix and adaptive coefficient estimation, respectively. From the figure, for both random entering and leaving interference, there are error floors when SNR $>$ 10 dB. However, if we adaptively estimate coefficients of

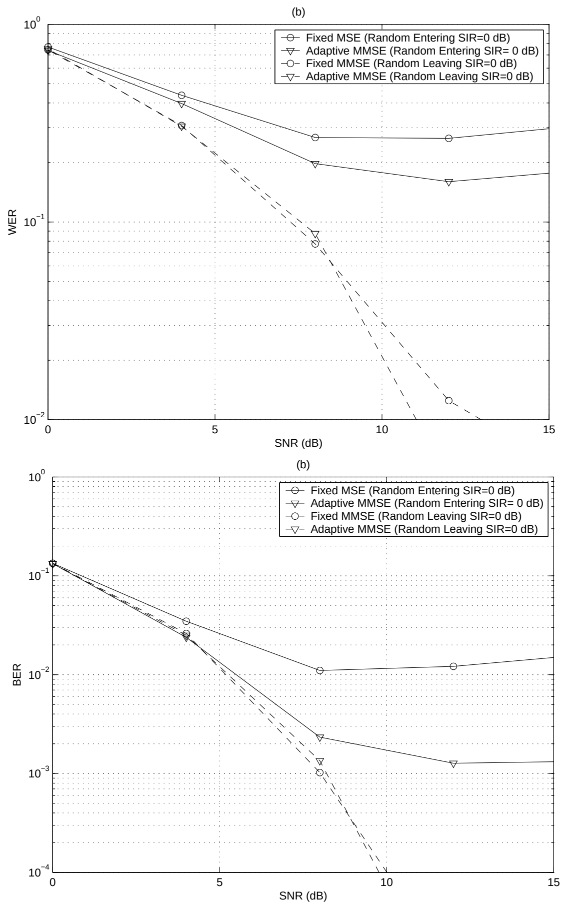

Fig. 5. Performance of interference suppression

the MMSE combiner using the pilots, performance can be significantly improved and the error floors disappear.

VI. Extension

Even though, we have focused on the system described in Section II, the proposed approaches can be used in any OFDM based UWB systems that can be modelled as

$$\underbrace{\begin{pmatrix} x_{1,n} \\ x_{2,n} \\ \vdots \\ x_{L,n} \end{pmatrix}}_{\mathbf{x}_n} = \underbrace{\begin{pmatrix} H_{1,n} \\ H_{2,n} \\ \vdots \\ H_{L,n} \end{pmatrix}}_{\mathbf{H}_n} c_n + \underbrace{\begin{pmatrix} i_{1,n} \\ i_{2,n} \\ \vdots \\ i_{L,n} \end{pmatrix}}_{\mathbf{i}_n}, \qquad (8)$$

or

$$\mathbf{x}_n = \mathbf{H}_n c_n + \mathbf{i}_n, \qquad (9)$$

for $n = 1, 2, \cdots, K$, where $i_{l,n}$ is interference. The interference statistics corresponding to different n's are correlated.

For an OFDM-based UWB system with repetition diversity, the same OFDM block is transmitted at different times and/or frequency bands. As a result, we have

$$x_{l,n} = H_{l,n} c_n + i_{l,n}, \qquad (10)$$

where $x_{l,n}$, $H_{l,n}$, and $i_{l,n}$ are the received signal, the channel's frequency response, and interference at the n-th tone of the l-th time and/or frequency repetition, c_n is the transmitted symbols at the n-th tone. It is obvious that the above equation can be written in matrix form as in Equation (8) or (9). Also note that the most recent version of the IEEE standards proposal [9] suggests frequency repetition and/or time repetition for different data rates (no repetition is foreseen for the 480Mbit/s mode). Also, the training sequences are repeated. None of those modifications affects the applicability of our analysis.

An OFDM based UWB system with receive antenna array can be also described by Equation (8) or (9). In that scenario, c_n is the transmitted symbol at the n-th tone, $x_{l,n}$ in Equation (8) or (9) represents the received signal from the n-th tone of the l-the antenna, $H_{l,k}$ represents the channel's frequency response at the n-th tone of the l-th receive antenna, and $i_{l,n}$ represents interference, inclduing co-channel interference and noise.

VII. Conclusions

We have developed low complexity and practical approaches for channel estimation and interference suppression for OFDM based UWB systems and demonstrated their effectiveness using computer simulation. The developed approaches can be directly used in future UWB communications for high data-rate home networks.

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