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Abstract

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***Abstract*— Ultra-wideband (UWB) communication is a potential technique for future high-speed networks. In this paper, we investigate channel estimation and interference suppression for OFDM based UWB systems. In particular, we modify an existing channel estimation approach for UWB systems and develop an exponential window based approach to estimate correlation of the receive signals for interference suppression. Computer simulation results show that these approaches can be effectively used in OFDM based UWB systems.**

***Index Terms*— UWB, OFDM, interference suppression, channel estimation.**

I. Introduction

ULTRA-WIDEBAND (UWB) communication has received great attention both by scientific community and by industry since a "report and order" of the *Federal Communications Commission* (FCC) 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 particular future home networks. Recognizing this potential, the IEEE has formed a 802.15.3a standardization group 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], [4]. However, within the IEEE 802.15.3a standardization group, *Orthogonal frequency-division multiplexing* (OFDM), combined with time-frequency interleaving [5], has emerged as a promising candidate. It is thus of great practical, as well as theoretical, interest to investigate 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. In this paper, we modify an existing channel estimation approach and invent a new approach to estimate statistics of interference for interference suppression.

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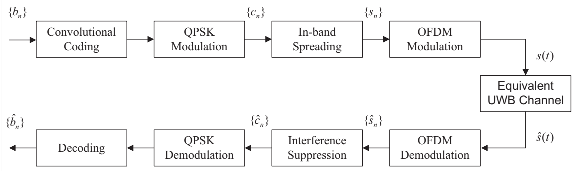

Fig. 1. Block diagram of an OFDM based UWB system.

II. System Description

Fig. 1 shows the block diagram of an OFDM-based UWB system, which closely follows the IEEE 802.15.3a proposal. The binary data stream to be transmitted is first encoded and interleaved (not shown here), and then converted into (complex) QPSK symbols, $\{c_n\}$. Each symbol is spread into two widely separated tones in the same OFDM block to exploit frequency diversity in UWB channels. 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

$$s(t) = \sum_{n=0}^{N-1} s_n e^{j2\pi f_n t}, \tag{2}$$

where $f_n = f_o + n\Delta f$, 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, different OFDM signals for the same user are transmitted through different frequency bands at different times for frequency diversity, as we can see from Fig. 3.

Due to delay spread of UWB channels and *multiple user interference* (MUI), the demodulated OFDM signal at the receiver can be expressed as

$$\hat{s}_n = H[n]s_n + i_n + n_n, \tag{3}$$

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

From (1), (3) can be also expressed as

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

or in a vector form as

$$\hat{\mathbf{s}}_n = \mathbf{H}[n]c_n + \mathbf{i}_n + \mathbf{n}_n, \tag{4}$$

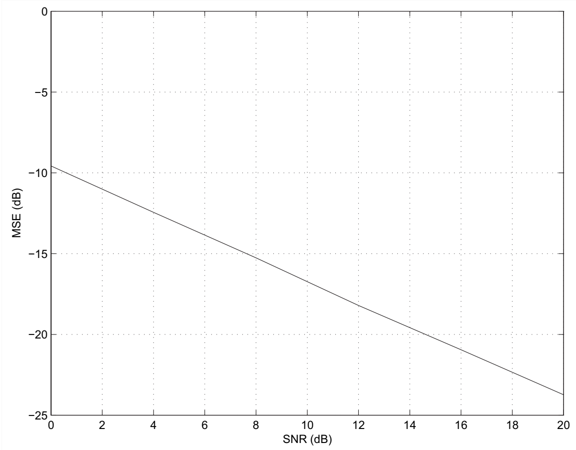

Fig. 2. Performance of Channel Estimation.

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

$$\hat{\mathbf{s}}_n = \begin{pmatrix} \hat{s}_n \\ \hat{s}_{n+N/2} \end{pmatrix}, \quad \mathbf{H}[n] = \begin{pmatrix} H[n] \\ \jmath H[n+N/2] \end{pmatrix}, \tag{5}$$

$$\mathbf{i}_n = \begin{pmatrix} i_n \\ i_{n+N/2} \end{pmatrix}, \quad \mathbf{n}_n = \begin{pmatrix} n_n \\ n_{n+N/2} \end{pmatrix}. \tag{6}$$

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 codeword 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, each for one of three subbands, are used for training. Hence, there are 246 OFDM blocks in total. 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 [5]. 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 [6], [7] 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, $r_m = \mathrm{E}\{H[n+m]H^*[n]\}$ (where the superscript "$*$" denotes the complex conjugate as usual), can be calculated. Using the correlation matrix, the channel parameters can be estimated by means of *singular value decomposition* (SVD) [7]. It is demonstrated in [6] 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, $\{s_n\}$, by

$$\tilde{H}[n] = \hat{s}_n s_n^* = H[n] + \tilde{n}_n, \tag{7}$$

where

$$\tilde{n}_n = i_n s_n^* + n_n s_n^*, \tag{8}$$

denotes the effect of interference and noise, and is independent for different n's. In (7), 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 *(inverse) 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

$$\hat{h}_k = \frac{p_k}{p_k + \Delta}\tilde{h}_k, \tag{9}$$

where p_k is determined by the correlation or delay profile of UWB channels and

$$\Delta = \frac{1}{N_2 - N_1 + 1}\sum_{k=N_1}^{N_2} |\tilde{h}_k|^2 \tag{10}$$

is the estimated interference-plus-noise power.

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

Fig. 2 demonstrates the *mean square-error* (MSE) versus *signal-to-noise ratio* (SNR) 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.

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

$$\begin{aligned} \hat{c}_n &= \frac{1}{\|\hat{\mathbf{H}}[n]\|}\hat{\mathbf{H}}^H[n]\hat{\mathbf{s}}_n. \\ &\approx \|\hat{\mathbf{H}}[n]\| c_n + \hat{n}_n, \end{aligned} \tag{11}$$

where the superscript "H" denotes the Hermitian of a vector or a matrix and $\hat{n}_n$ denotes the effect of noise that can be expressed as

$$\hat{n}_n = \frac{\hat{H}^*[n]\tilde{n}_n + \hat{H}^*[n+N/2]\tilde{n}_{n+N/2}}{\|\hat{\mathbf{H}}[n]\|}. \tag{12}$$

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.

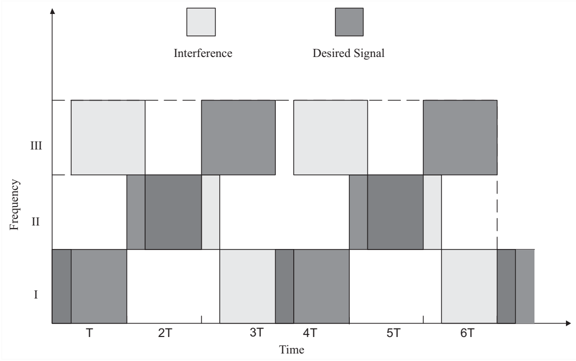

Fig. 3. Time-frequency hopping with interference.

IV. Interference Suppression

The IEEE 802.15.3a system has two types of multiple access. For devices within the same piconet, TDMA is used, causing no interference. Different piconets may also operate in the same area, which differ only by the use of different time-frequency interleaving codes and do not coordinate the timing of the transmission (un-cooperative piconets). Thus, interference is unavoidable. Fig. 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 the interferer and the desired users. Let the power ratio of the desired user to interference user be SIR. Due to the difference of time-frequency hopping patterns, the power ratio of the desired user and the effective interference (the overlapped area in Fig. 3) is reduced to

$$\mathrm{SIR}_e = \frac{1}{3}\mathrm{SIR}, \quad \text{or} \quad \mathrm{SIR}_e\ (\mathrm{dB}) = \mathrm{SIR} - 4.8\ (\mathrm{dB}). \tag{13}$$

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 [8] can be used here for interference suppression. From [8], the optimum coefficient vector that minimizes the MSE of the combiner output is determined by

$$\mathbf{w}_n = \mathbf{R}_n^{-1}\mathbf{d}_n, \tag{14}$$

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

$$\mathbf{R}_n = \mathrm{E}\{\hat{\mathbf{s}}_n\hat{\mathbf{s}}_n^H\}, \tag{15}$$

and

$$\mathbf{d}_n = \mathrm{E}\{\hat{\mathbf{s}}_n s_n^*\} = \begin{pmatrix} H[n] \\ \jmath H[n+N/2] \end{pmatrix}, \tag{16}$$

respectively.

The estimation of the correlation matrix was investigated in [8] for flat fading channels and in [9] for OFDM with frequency-selective channels. We have tried to apply the approach in [9] 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.

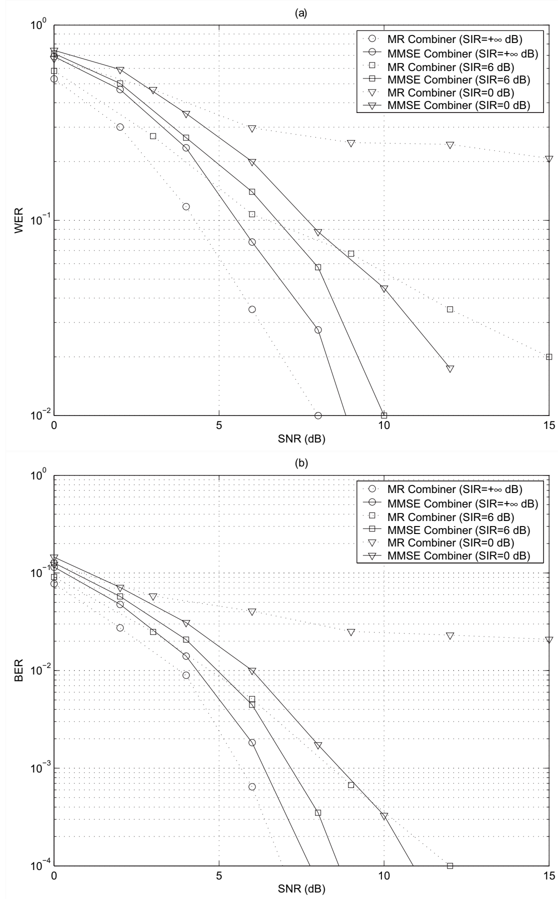

Fig. 4. Performance comparison of the MR and the MMSE diversity combiners.

During the training OFDM block, the transmitted symbols, $\{s_n\}$ are known to the receiver. Then the coefficient vector, $\mathbf{w}_n$ can be found to minimize the following cost function,

$$\mathcal{C}(\mathbf{w}_n) = \frac{1}{\sum_k \lambda^{|n-k|}} \sum_k \lambda^{|n-k|} |\mathbf{w}_n^H \hat{\mathbf{s}}_k - s_k|^2, \tag{17}$$

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

$$\hat{\mathbf{w}}_n = \hat{\mathbf{R}}_n^{-1}\hat{\mathbf{d}}_n, \tag{18}$$

where

$$\hat{\mathbf{R}}_n = \frac{1}{\sum_k \lambda^{|n-k|}} \sum_k \lambda^{|n-k|} \hat{\mathbf{s}}_k \hat{\mathbf{s}}_k^H, \tag{19}$$

and

$$\hat{\mathbf{d}}_n = \frac{1}{\sum_k \lambda^{|n-k|}} \sum_k \lambda^{|n-k|} \hat{\mathbf{s}}_k s_k^*. \tag{20}$$

With the estimated coefficient vector, the received signals can

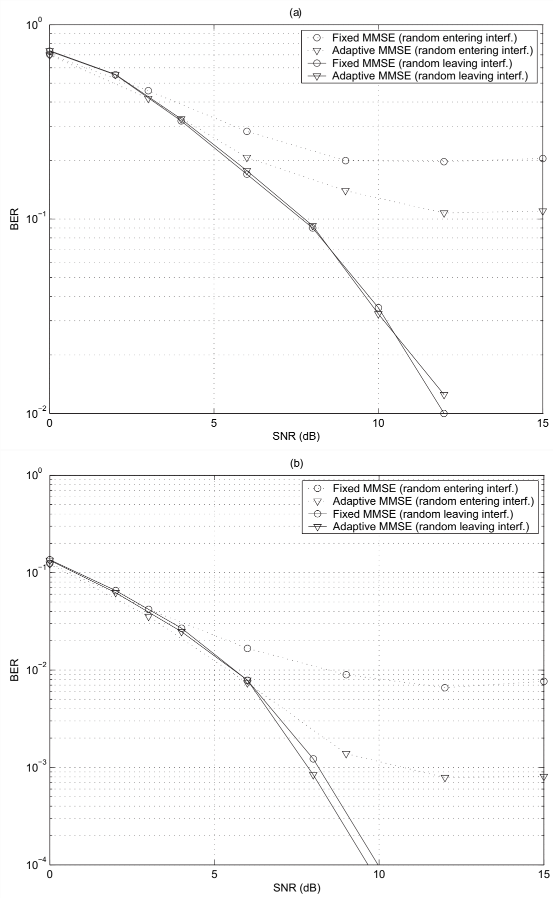

Fig. 5. Performance of random entering and leaving interference suppression.

be combined by

$$\hat{c}_n = \frac{1}{\sqrt{\mathcal{C}(\hat{\mathbf{w}}_n)}} \hat{\mathbf{w}}_n^H \hat{\mathbf{s}}_n = \frac{1}{\sqrt{1 - \hat{\mathbf{w}}_n^H \hat{\mathbf{d}}_n}} \hat{\mathbf{w}}_n^H \hat{\mathbf{s}}_n. \quad (21)$$

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 Section 2. Fig. 4 compares the *word-error-rate* (WER) and the *bit-error-rate* (BER) of the MR and the MMSE combiners, respectively, where each packet, containing 8096 information bits, is a word. From the figure, the performance of the MR combiner is better than that of the MMSE combiner when there is no interference. The MR and the MMSE combiners should be equivalent if both uses the exact coefficients for diversity combining. Because more accurate coefficients for the MR combiner can be estimated, it has better performance than the MMSE combiner if estimated coefficients are used. Since the MR combiner treats interference as AWGN and does not exploit the correlation of interference, the performance of the MMSE combiner catches up and then outperforms that of the MR combiner with the decrease of the *signal-to-interference ratio* (SIR). The required SNR's for 10% WER or 1% BER for the MR and the MMSE combiners are almost same when SIR=6 dB. The performance of the MMSE combiner is much better than that of the MR combiner when the desired signal power equals that of interference, corresponding to SIR=0 dB.

V. Random Interference Suppression

In UWB systems, each slot/package contains about a hundred OFDM blocks. As different piconets (users with different time-frequency codes) are uncoordinated, the interference statistics might change during the transmission of a packet. If an interference user finishes transmission during a time slot of the desired user, then the existing interference will disappear, which is called *random leaving interference*. On the other hand, an interference user may start transmission during a time slot, which generates *random entering interference*. In either case, we need to adaptively change the coefficients of the MMSE combiner according to interference environments.

There are 12 pilot tones for each OFDM block in Strawman's proposal [5]. 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.

Fig. 5 demonstrates the performance of the MMSE combiners with fix and adaptive coefficient estimation, respectively. From the figure, for random entering interference, the MMSE combiner with adaptive coefficient reduces the BER floor from about 10^{-2} to 10^{-3} while for random leaving interference, the MMSE combiners with both adaptive and fixed coefficients have similar performance.

VI. Conclusions

We have developed practical approaches to 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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