A Study of Channel Estimation in Multi-Band OFDM UWB Systems

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Abstract

In this paper, the channel estimation techniques for multi-band (MB) OFDM ultra-wideband (UWB) wireless communications are investigated. By combining orthogonal frequency-division multiplexing (OFDM) with multi-band, the MB-OFDM systems can capture multi-path energy more efficiently than single-band direct-sequence UWB (DS-UWB). However, most researches for UWB channel estimation are focused on the latter. Through the analysis of architecture, signal and channel model of MB-OFDM UWB wireless systems, we studied the channel estimation techniques based on preamble training sequences and pilot sub-carriers respectively. Further more, the linear estimations of least square (LS) and minimum mean square error (MMSE) are analyzed and compared under different UWB channel conditions. The characteristic of estimation error changing with the SNR is also discussed. The estimation error includes the impact of interpolation error and channel noise.

1. Introduction

Under the condition of indoor short-range wireless transmission, the UWB systems can provide very high data rate whereas the power consumption is very low, which makes it a promising candidate for wireless personal area networks (WPAN) where the data rate is greater than 110Mbps and the range is shorter than 10 meters in general. Moreover, UWB is also introduced into the underlying transport mechanism of wireless USB and wireless 1394 for even higher throughput up to 480Mbps within 2 meters [1].

The UWB systems based on MB-OFDM divide the whole assigned spectrum into several smaller sub-bands and each sub-band into a few sub-carriers to transmit the information, which leads to lower design complexity as well as better spectral efficiency and flexibility than the DS-UWB systems [1] [2] [3]. In particular, for highly dispersive channels in the dense multi-path environment, an MB-OFDM UWB receiver is more efficient at capturing multi-path energy and more robust against inter-symbol interference (ISI) than an equivalent single-carrier system using the same total bandwidth.

Channel estimation is a very important issue for coherent OFDM systems. Generally, the MB-OFDM UWB systems adopt continuous modulation rather than differential modulation in considering of saving transmission power and providing relatively high data rates. Hence, coherent detection is required in receiver, which needs an estimation and compensation of the channel impulse response (CIR) before the demodulation. Channel estimation can be avoided by using differential modulation, but there is a 3dB loss in signal-to-noise ratio (SNR) approximately [4]. The result of channel estimation is also used in diversity combination and optimization of the receiver performance. Due to the time-frequency two-dimension grid structure of OFDM signal, the channel estimator is allowed to use both time and frequency correlation [5]. However, such an estimator structure is generally too complex for a practical implementation. The channel estimation techniques based on block type and comb type pilot arrangement are analyzed in [6]. In [7], the performance of comb-type estimator and block-type estimator is compared for indoor channels that have low frequency selectivity relatively. The performance of least square (LS) and minimum mean-square error (MMSE) estimators is analyzed in [4] [6] [8]. In practice, there are many differences between the behavior of narrow-band and UWB systems [3]. A channel estimation approach exploiting the correlations of different tones is proposed in [9], which is considered as a simple scheme that can be employed in UWB systems.

The paper is organized as follows: After presenting the OFDM architecture and system model in Section 2, we introduce the approaches of channel estimation and the theoretical investigation in Section 3. We focus on two classes of channel estimation techniques that based on training sequence and pilot tones, combined with two kinds of linear estimation criterion: LS and MMSE. Furthermore, the performance of these approaches is compared under different UWB channel conditions. The change of estimation error under different SNR is investigated, too. Simulation results computed out in Section 4 are compared and analyzed. Section 5 concludes the paper.

2. System description

2.1. Architecture of an MB-OFDM UWB system

The baseband and modulation structure of OFDM based UWB transmitter is shown in Figure 1.

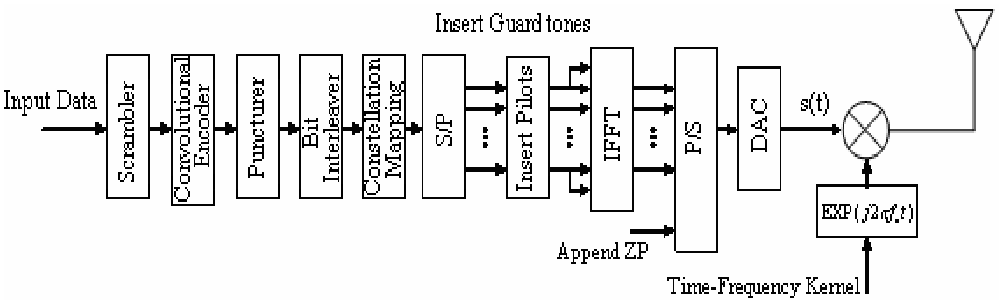

Figure 1. TX architecture for MB-OFDM UWB system

After scrambling, encoding/puncturing and bit interleaving, the binary serial data shall be mapped into constellation points according to the Gray-coding. Here, continuous modulation such as quadrature phase- shift keying (QPSK) is recommended. Then the stream of complex symbols is mapped into coefficients of IFFT [10]. For low complexity solution, an FFT size of 256 points is too big. However, a FFT size smaller than 64 points will increase the overhead due to zero-padded (ZP) suffix. An optimal FFT size for UWB system is 128, which provides a balance between performance and complexity [3].

Out of the 128 sub-carriers in each OFDM symbol, 100 are allocated to data and 12 are dedicated to pilots uniformly inserted into the OFDM symbol. The 10 guard subcarriers, with five on either edge of the OFDM symbol occupied band, are created by copying the five outermost data subcarriers. The rest six IFFT input are set to zero. After performing the IFFT, a ZP suffix of length 37 is appended to eliminate ISI and capture sufficient multi-path energy to minimize the impact of inter-carrier interference (ICI). A time-frequency kernel is used to specify the centre frequency for transmission of each OFDM symbol. In the receiver, the channel estimation sequence (CES) in preamble and the pilots picked out from the OFDM symbols are used for channel estimation [10].

2.2. Signal model

OFDM transmitter converts input information into N (=128) parallel data sequences, then modulated by IFFT in baseband and then, converted back into serial sequence [10]. The kth OFDM symbol in the form of complex baseband signal has the following expression

$$s_k(t)=\begin{cases}\sum_{n=-N/2}^{N/2} C_n \exp(j2\pi n\Delta_f t) & t\in[0,T_{FFT}] \\ 0 & t\in[T_{FFT},T_{FFT}+T_{ZP}]\end{cases} \quad (1)$$

where Δ_f is the frequency spacing of the N subcarriers. The coefficients C_n represent either data, pilots, or guard tones. $T_{FFT}=1/\Delta_f$ is the duration of OFDM symbols and T_{ZP} is the period of ZP.

The transmitted RF signal is described as [2]

$$s_{RF}(t)=\mathrm{Re}\left\{\sum_{k=0}^{K-1} s_k\left(t-kT_{SYM}\right)\exp\left(j2\pi f_{(k \bmod 6)}t\right)\right\} \quad (2)$$

where T_{SYM} is the OFDM symbol interval, and K is the number of OFDM symbols transmitted. The 7.5GHz UWB spectrum is divided into 14 sub-bands that are 528MHz wide each and the data is transmitted across these sub-bands using a time-frequency code (TFCs). Only band group1 (3.1-4.8GHz) is used which consists of 3 sub-bands since increasing the upper frequency past 4.8GHz will lead to higher complexity and power consumption in current CMOS technology. The 3 sub-bands are organized into 4 TFCs of length 6 to provide multiple access and frequency diversity. Each of the three sub-bands is tied to one service.

2.3. Channel model

The time of arrival of multi-path components is not continuous and represents the characteristic of "clustering" [11] [12]. Here, a lognormal distribution rather than a Rayleigh distribution is recommended to describing the received envelope and multi-path gain magnitude. The Saleh-Valenzuela (S-V) multi-path model is unique in modelling arrivals in clusters, as well as rays within a cluster. With minor modifications to the S-V model, the multi-path UWB channel impulse response in discrete time form can be expressed as

$$h_i(t) = X_i \sum_{l=0}^{L} \sum_{k=0}^{K} \alpha_{k,l}^i \delta(t - T_l^i - \tau_{k,l}^i) \quad (3)$$

where i refers to the impulse response realization, l refers to the cluster, and k refers to the ray within the cluster, $\alpha_{k,l}^i$ is the multi-path gain coefficient conforming to the lognormal distribution; T_l^i is the delay of the lth cluster; $\tau_{k,l}^i$ is the delay of the kth ray relative to T_l^i ; X_i represents the lognormal shadowing. The ability of UWB receiver to resolve multi-paths is significantly increased for the large bandwidth.

3. Channel estimation

At the receiver, the demodulated OFDM signal after FFT can be expressed in matrix notation

$$Y = XFh + I + W \quad (4)$$

where ***X*** is the matrix of transmitted signal, ***h*** is time domain channel impulse response, ***I*** is ISI and ICI, ***W*** is Additive White Gaussian Noise (AWGN) with zero-mean and variance N_0, ***F*** is the DFT matrix, ***H*** =***F*** · ***h*** is the channel frequency response. Here,

$$\boldsymbol{X} = diag\{X(0), X(1), \cdots X(N-1)\}$$

$$\boldsymbol{Y} = [Y(0), Y(1), \cdots, Y(N-1)]^{\mathrm{T}}$$

$$\boldsymbol{W} = [W(0), W(1), \cdots, W(N-1)]^{\mathrm{T}}$$

$$\boldsymbol{H} = [H(0), H(1), \cdots, H(N-1)]^{\mathrm{T}}$$

$$\boldsymbol{F} = \begin{bmatrix} W_N^{00} & \cdots & W_N^{0(N-1)} \\ \vdots & \ddots & \vdots \\ W_N^{(N-1)0} & \cdots & W_N^{(N-1)(N-1)} \end{bmatrix}$$

$$W_N^{nk} = \frac{1}{N} \mathrm{e}^{-j2\pi(n/N)k}$$

Considering the length of ZP is larger than the maximum delay spread of the UWB channel [3], the ISI is effectively suppressed. At the same time, assuming perfect frequency synchronization, the ICI is negligible. Then, the received signal can be written as

$$Y = XFh + W \quad (5)$$

The expression of frequency domain LS estimation is

$$H_{LS} = X^{-1}Y \quad (6)$$

which minimizes $(Y - XFh)^H (Y - XFh)$.

Assuming the vector ***h*** is Gaussian and uncorrelated with the channel noise ***W***. The frequency domain MMSE estimate can be represented by

$$H_{MMSE} = FR_{hY}R_{YY}^{-1}Y \quad (7)$$

where $R_{hY} = E[hY] = R_{hh}F^H X^H$ is the cross covariance matrix between ***h*** and ***Y***, $R_{YY} = E[YY] = XFR_{hh}F^H X^H + \sigma^2 I_N$ is the auto-covariance matrix of ***Y***. R_{hh} is the auto-covariance matrix of ***h*** and σ^2 is the noise variance. The MMSE estimation has better performance than LS estimation for exploiting the prior information on channel statistics, however the computational complexity is higher consequently [4].

In every packet with a sequence of OFDM symbols multiplexed onto, training symbols are added in the preamble part and a few pilot symbols are inserted in each OFDM symbol. The channel estimation of OFDM based UWB systems can be performed by, either adopting preamble training sequence or inserting pilots into each OFDM symbol.

In the training sequence assisted channel estimation, the channel should be regarded as slow fading and not time-variant over the packet period [6]. The CES is constructed by successively appending six periods of known OFDM symbols at best. The estimation can be based on LS or MMSE and used for the channel state information (CSI) at all sub-carriers. The estimations remain available for the rest data of the packet so long as the channels are not changed.

The pilots assisted channel estimation has been introduced when the channel changes even in one OFDM block. To this purpose, known pilots are often multiplexed into the OFDM symbols. This approach consists of algorithms to estimate the channel at pilot sub-carriers and to interpolate the channel at data sub-carriers. The transmitted samples can be represented by

$$X(k) = X(mL + l) = \begin{cases} x_p(m) & l = 0 \\ d(m) & l = 1, \ldots, L-1 \end{cases} \quad (8)$$

where L is the interval between pilot and $x_p(m)$ is the mth pilot.

The estimation at the pilot sub-carriers can be also based on LS or MMSE. There are several methods of interpolation to estimate channel at data sub-carriers. The second-order interpolation is given by

$$H_e(k) = H_e(mL + l) = c_1 H_p(m-1) + c_0 H_p(m) + c_{-1} H_p(m+1) \quad (9)$$

where $mL<k<(m+1)L$, $0<l<L$, c_1 , c_0 and c_{-1} are determined by l/L . Similarly, the linear interpolation can be expressed as combination of estimation on two

adjacent pilot sub-carriers. The spline cubic interpolation provides a polynomial to make the channel estimated at pilots fitted smoothly and continuously. The low-pass interpolation inserts zeros into an original sequence and then applies a low-pass FIR filter in the frequency domain to reduce the noise level, which minimizes the MSE between the interpolated points and their ideal values. The time domain interpolation first converts the estimation at pilots into time domain form by IDFT and then appends zero padding in given positions, the estimation at all sub-carriers is obtained by DFT finally [6].

However, the CSI interpolated for data sub-carriers are not true estimation, and the performance depends on the frequency selectivity of the channel. If the number of pilot sub-carriers is less than the CIR length, the mean square error (MSE) of estimation observably increases. On the other hand, over many pilot sub-carriers lead to the spectrum efficiency decline. Assuming there are no ISI and ICI, the MSE of the channel estimation is

$$\varepsilon = \varepsilon_I + \varepsilon_N \qquad (10)$$

where ε_I is the interpolation error and ε_N is dependent on the AWGN and pilots interval L. To reduce the value of ε_I, frequency selectivity of channel between pilot sub-carriers should be decreased [7]. Here, $\varepsilon_N \le N_0$ for the effect of noise reduction by the interpolation. When L=1 corresponding the case of training sequence assisted estimation, ε_I =0.

4. Simulation results

The system parameters are shown in Table 1. We assume that there is no synchronous error. The Doppler spread can be regarded as zero since the application of UWB system is usually on immobile occasion. In our simulation, CM1 and CM2 are adopted, which respectively based on line-of-sight (LOS) and non-line-of-sight (NLOS) in the range of 0-4m [11].

Table 1. System parameters

Parameters	Specification
FFT Size	128
Number of Data Tones	100
Number of Pilot Tones	12
Number of Guard Tones	10
Bandwidth of sub-bands	528MHz
Data Rate	200Mbps
Channel Code	Convolutional, 5/8
Constellation	QPSK
Time-domain Spreading factor	2
Channel Model	CM1，CM2

In the training sequence assisted approach of channel estimation, the performance of BER has been compared according to LS and MMSE under the LOS (0-4m) and NLOS (0-4m) channel environments respectively. From Figure 2 we can see that MMSE shows better performance than LS. Given the same SNR, the BER under NLOS channel is higher than that under LOS channel because the impact of multi-path propagation in NLOS channel is more significant.

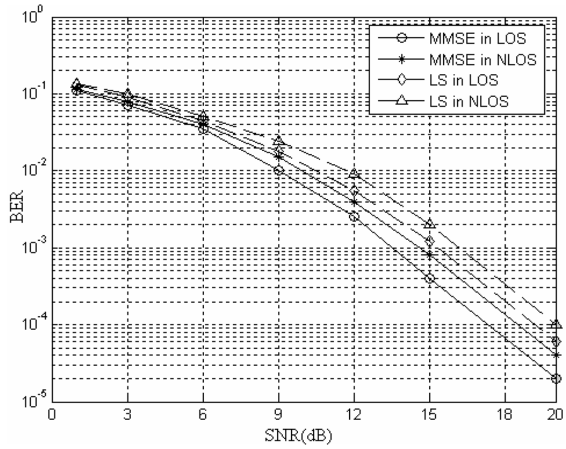

Figure 2. Training sequence assisted channel estimation

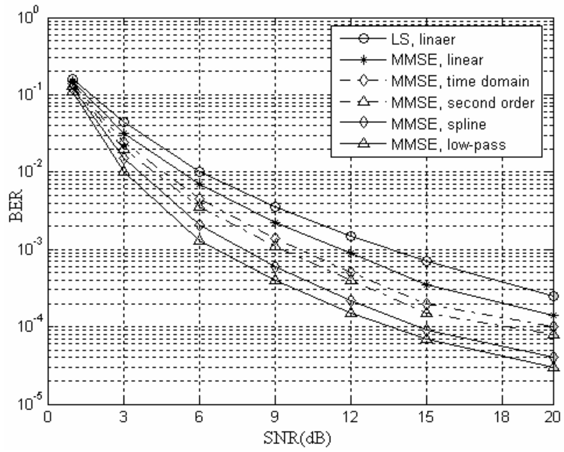

Figure 3. Pilots assisted channel estimation

In the pilots assisted approach of channel estimation, the performance of BER has been compared when adopting several interpolations under LOS channel. Figure 3 shows that the performance of linear, second-order and spline cubic interpolation is increasing with the order, due to the nature that the higher-order interpolation fits the given data points more smoothly. The performance of time domain interpolation is between the linear and second-order interpolation. The performance of low-pass interpolation is the best in all of the interpolation methods for its high resolution. If the same method of interpolation (e.g. the linear interpolation) is applied, the BER performance of MMSE is better than that of LS, since LS estimation is susceptible to noise and ICI.

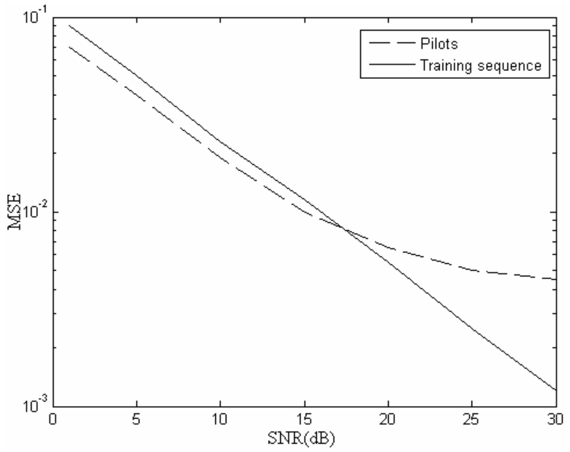

Figure 4. MSE versus SNR for training sequence and linear interpolation

Figure 4 shows the impact of different SNR on the MSE of training sequence estimation and linear interpolation. The performance for pilots assisted approach outperforms that of training sequence approach under low SNR since the interpolation can reduce the noise. Thereby, as the SNR increase, the pilots approach exhibits an irreducible error floor due to the interpolation error. For high SNR, the MSE of training sequence approach is less than that of pilots approach because the effect of noise reduction by interpolation becomes insignificant and the effect of interpolation error is dominant here. The rule of impact caused by estimation error changed with the SNR exhibits in Figure 5 and Figure 6, too.

In Figure 5, the performance of BER has been compared between estimation approaches of training sequence and pilots assisted (linear interpolation) according to LS under the LOS (0-4m) and NLOS (0-4m) channel environments. The time delay spread under NLOS (0-4m) channel is larger than that of LOS (0-4m) channel [11], therefore the frequency selectivity between sub-carriers of NLOS is more serious than that of LOS.

In Figure 6, the performance of BER has been compared between LS and MMSE estimation adopting approaches of training sequence and pilots assisted (low-pass interpolation) under the LOS (0-4m) channel environments. Although the performance of MMSE is better than LS, for relative low SNR, the LS estimation with low-pass interpolation can satisfy the requirement of coherent detection and that the computational complexity is reduced.

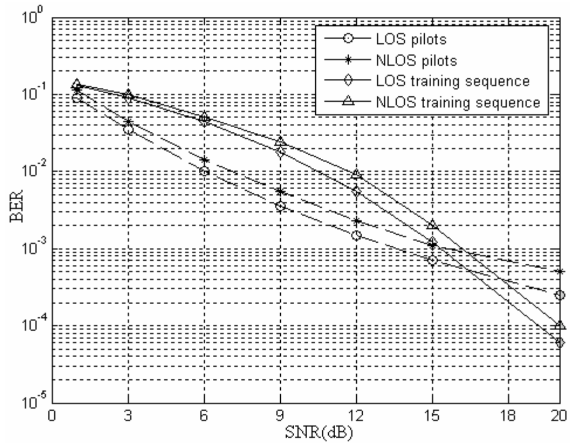

Figure 5. Performance comparison for approaches of training sequence and pilots

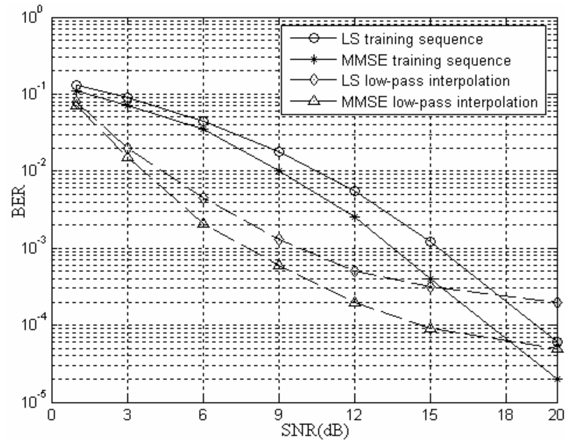

Figure 6. Performance comparison for LS and MMSE of low-pass interpolation and training sequence

5. Conclusions

In this paper, a full view of architecture, signal and channel model of OFDM based UWB system is given. We have investigated the feasible approaches of channel estimation based on training sequence in preamble and pilot sub-carriers in the OFDM symbols. The MSE performance of these two approaches is also compared under different SNR. The performance of LS and MMSE estimators is compared under the condition of UWB channel model CM1 and CM2. We also compared the performance of different interpolation techniques in pilots assisted channel estimation. These results can be applied in the UWB communications to achieve better receiving performance.

6. Acknowledgement

This work was supported by Shanghai Leading Academic Discipline Project. Project Number: T0102.

7. References

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