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OFDM Channel Estimation using a MMSE Estimator of a Comb-type System

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Abstract

Orthogonal frequency division multiplexing (OFDM) is a key technique for wireless communication because of its robustness for narrow band interference, frequency selective fading and spectral efficiency. Channel estimation and equalization in OFDM is necessary in order to nullify the effect of impairments induced by the frequency selective fading channel. Frequency domain comb type pilot assisted channel estimation has been implemented for the channel estimation purpose. Modified Minimum Mean Square Error (MMSE) estimator is considered for estimation of the channel at pilot subcarriers. The performance and complexity comparison is made between the modified MMSE and MMSE estimator for fast fading Rayleigh channel. Linear, Low Pass and spline cubic interpolation techniques have been used with the proposed modified MMSE estimator. The effect of increase in number of channel taps on the performance of both estimators has been studied.

Keywords

Co-channel interference, communication channels, data communication, digital communication, frequency division multiplexing, frequency domain analysis, time domain analysis, time-varying channels.

1. Introduction

Bandwidth efficiency and robustness to channel impairments have made orthogonal frequency division multiplexing (OFDM) technique an attractive feature for wireless communication standards. OFDM is used widely in applications i.e. Wi-Fi, Wi-MAX and power line communications [1]. Broadcasting standards i.e. Digital Multimedia Broadcasting (DMB) and Digital Video Broadcasting -terrestrial (DVB-T) are using OFDM [2].

In OFDM, frequency selective fading channel is transformed to flat fading channel by the division of the available channel bandwidth into several sub channels. Improvisation in the performance of the OFDM system can be done in thepresence of frequency selective fading channel through the use of channel estimation and equalization. In single carrier communication systems, complex equalization techniques are used for inter symbol interference (ISI) cancellation; however OFDM uses cyclic prefix for ISI mitigation [3].

Semi-blind, blind and pilot-aided channel estimation is the three categories of channel estimation. The information about the channel state is estimated through the use of received signal statistics. Pilot tones are used in pilot-aided channel estimation for the estimation of the channel impulse response. Semi-blind channel estimation is the combination ofpilot aided and blind channel estimation. The channel estimation capabilityof blind estimation can be enhanced through the use of pilots [4]. In [5], comb-type pilot assisted channel estimation over Rayleigh fading channel is used. The interpolation technique proposed in [5] has been compared with time domain [6] and second order interpolation technique. Minimum mean square error (MMSE) estimator outperforms least square (LS) estimator [7][8].MMSE estimator uses prior information about the channel statistics.

1D comb-type channel estimation is considered because of its low computational complexity as compared to 2D channel estimation. Modified MMSE channel estimator is used for estimation of channel at pilot sub-carriers. The performance comparison between the modified MMSE estimator and conventional MMSE estimator is made for channels of different number of taps. So far, the performance of the modified MMSE estimator remains fine for an increase in number of taps, however performance degradation occurs for conventional MMSE estimator with an increase in channel taps.

Notation: I_p stands for $P \, X \, P$ identity matrix. Subscripts ^{T} and ^{H}represents the transpose and Hermitian transpose.

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2. System Overview

The OFDM system model with channel estimation is shown in fig.1 below. The input bits are mapped and parallelized. To nullify the effects of the multipath fading channel, it is necessary to effectively estimate the channel frequency response. A MMSE estimator to estimate the channel impulse response at pilot subcarriers has been used. Finally after channel estimation and equalization, the signal is de-mapped to yield the output bits.

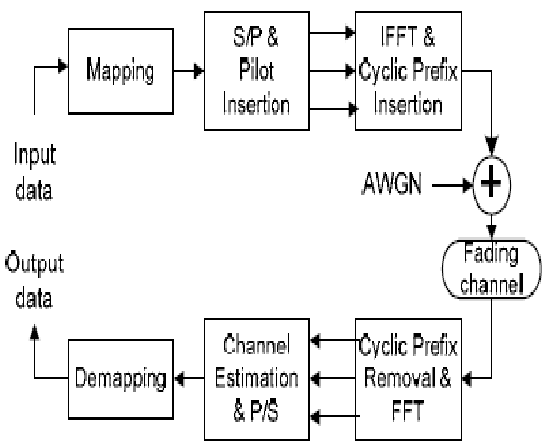

fig.1: OFDM System with Comb-type Channel Estimation

3. Channel Estimation and Interpolation Techniques

One dimensional (1D) Channel estimation in OFDM has two common types i.e. block-type and comb-type;based upon the arrangement of pilots. Block-type channel estimation is used for slow fading channels while comb-type is best suited for fast fading channels. Arrangement of pilots for comb-type and block-type channel estimation is shown in fig.2. A comb-type channel estimation has been used because of the use of the fast fading Rayleigh channel for performance analysis of the OFDM system. Equi-spaced pilot insertion is adopted because of optimum performance [10]. The channel frequency response at pilot subcarrier is estimated by using MMSE estimator because of its superior performance as compared to least square (LS) estimator [7][8].

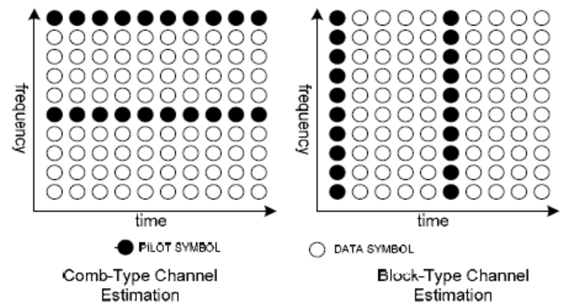

fig.2.Arrangement of Pilots

A. Channel Estimation at Pilot Frequencies

In comb-type pilot based channel estimation, the $'N_p'$ pilot signals are uniformly inserted into X(k) according to the following equation:

X(k) = X(mL+l)

$$= \begin{cases} x_p(m), l = 0 \\ inf\ data\ l = 1, \dots\dots L-1 \end{cases} \dots\dots.(1)$$

where L= number of carriers/N_P and $x_p(m)$is the nth pilot carrier value. It is defined,$\{H_P(k) = 0,1,\dots\dots N_p\ \}$as the frequency response of the channel at pilot sub-carriers. The estimate of the channel at pilot sub-carriers based on LS estimation is given by-

$$H_c = \frac{Y_P(k)}{X_P(k)} \quad k = 0,1,\dots..N_{p-1} \dots\dots\dots\dots(2)$$

where,$Y_P(k)$ and $X_P(k)$ are output and input at the kth pilot sub-carrier respectively.

Since LS estimate is susceptible to noise and ICI, MMSE is thought about while compromising complexity. Since MMSE includes the matrix inversion at each iteration, the simplified linear MMSE estimator is suggested in [12]. In this simplified version, the inverse is only need to be calculated once. In [13], the complexity is further reduced with a low-rank approximation by using singular value decomposition.

B.Interpolation Techniques

The channel estimation based on comb type pilot insertion, an interpolation technique is necessary in order to estimate channel at data sub-carriers by using the channel information at pilot sub-carriers.

The linear interpolation method gives better results than the piecewise-constant interpolation in [7]. The channel estimation at the data-carrier ‘k’,mL<k<(m+1)L,using linear interpolation is given by:

$$H_e(k) = H_e(mL+l)\,, \qquad 0 \le l < L$$
$$= \left(H_p(m+1) - H_P(m)\right)\frac{l}{L} + H_P(m)$$
…………..(3)

The second-order interpolation results to be better than the linear interpolation [13]. The channel estimated by second-order interpolation is given by:

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

where, $\begin{cases} c_1 = \frac{\alpha(\alpha-1)}{2} \\ c_0 = -(\alpha-1)(\alpha+1), \alpha = \frac{1}{N} \\ c_{-1} = \frac{\alpha(\alpha+1)}{2} \end{cases}$ ………………..(4)

The low-pass interpolation is performed by inserting zeros into the original sequence and then applying a lowpass FIR filter (*interp function in MATLAB*) that allows the original data to pass through unchanged and interpolates between such that the mean-square error between the interpolated points and their ideal values is minimized. The spline cubic interpolation (*spline function in MATLAB*) produces a smooth and continuous polynomial,fitted to given data points. The time domain interpolation is a high-resolution interpolation based on zero-padding and DFT/IDFT [8].After obtaining the estimated channel $\{H_P(k) = 0,1,\ldots\ldots N_p\text{-}1\}$,it is first converted to time domain by IDFT:

$$G(n) = \sum_{k=0}^{N_p-1} H_p e^{j(2\pi kn/N_p)} \quad ,n = 0,1,\ldots\ldots N_p - 1$$
…………..(5)

Then, by using the basic multi-rate signal processing properties [9], the signal is interpolated bytransforming the N_p points into N points with the following method:

$$M = \frac{N_p}{2} + 1$$
$$G(N) = \begin{cases} G_p, \ 0 \le n < M-2 \\ 0, \frac{N_P}{2} \le N - m \\ G_p(n-N+2M-1), -M \le n-N < -1 \end{cases}$$
………………….(6)

The estimate of the channel at all frequencies is obtained by:

$$H(k) = \sum_{n=0}^{N-1} G_N(n) e^{-j\left(\frac{2\pi}{N}\right)nk}, 0 \le k \le N-1$$
……………..(7)

4. Simulation

A. Description of Simulation

(i) System Parameters :

OFDM system parameters used in the simulation are indicated in Table I.It is assumed to have perfect synchronization since the aim is to observe channel estimation performance. Moreover, the guard interval has been chosen in such a way that it is greater than the maximum delay spread in order to avoid inter-symbol interference. Simulations are carried out for different signal-to-noise (SNR) ratios and for different Doppler spreads.

Table I: Simulation Parameters

Parameters	Specifications
FFT size	1024
No.of active carriers(N)	128
Pilot Ratio	1/8
Guard Interval	256
Guard Type	Cyclic extension
Sample Rate	44.1 kHz
Bandwidth	17.5 KHz
Signal Constellation	BPSK,QPSK,DQPSK,16QAM
Channel Model	Rayleigh Fading,AR Model

(ii) Channel Model:

Two multi-path fading channel models
are used in the simulations. The 1st channel model is the ATTC (Advanced Television Technology Center) and the Grande Alliance DTV laboratory’s ensemble E model, whose static case impulse response is given by:

h(n)=α(n)+0.3162α(n-2)+0.1995α(n-17)+01296α (n-36)+0.1α(n-75)+0.1α(n-137)
……………(8)

The 2nd channel model is the simplified version of DVB-T channel model, whose static impulse response is given in Table II. In the simulation, Rayleigh fading channel has been used. In order to see the effect of fading on comb type based and LMS based channel estimation,a channel has been modeled which is time-varying according to the following autoregressive (AR) model:

h(n+1)=αh(n)+w(n) ………………..(9)

where ‘α’ is the fading factor and w(n) is AWGN noise vector which is chosen to be close to 1 in order to satisfy the assumption that channel impulse response does not change within one OFDM symbol duration. In the simulations, changes from 0.90 to 1 is taken in to consideration.

Table II: Channel Impulse Response for channel 2

Delay(OFDM samples)	Gain	Phase(rad)
0	0.2478	-2.5649
1	0.1287	-2.1208
3	0.3088	0.3548
4	0.4252	0.4187
5	0.49	2.7201
7	0.0365	-1.4375
8	0.1197	1.1302
12	0.1948	-0.8092
17	0.4187	-0.1545
24	0.317	-2.459
29	0.2055	2.8372
49	0.1846	2.8641

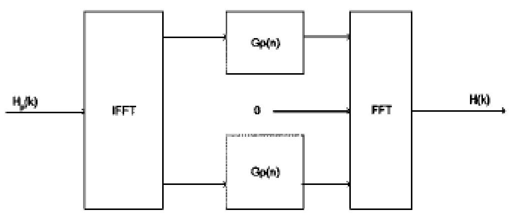

fig. 3: Time domain interpolation

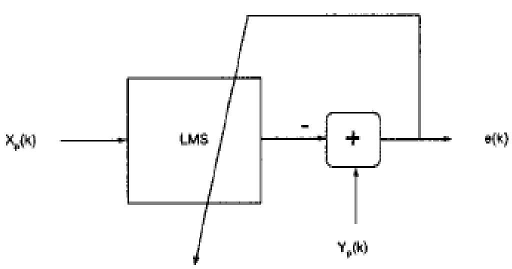

fig. 4: LMS scheme

(iii) Channel Estimation Based on Block-Type Pilot Arrangement:

Two types of block-type pilot based channel estimation has been modeled. Each block consists of a fixed number of symbols, which is 30 in the simulation. Pilots are sent in all the sub-carriers of the first symbol of each block and channel estimation is performed by using LS estimation. According to the first model, the channel estimation is done at the beginning of the block , used for all the symbols of the block and according to the second method, the estimation is done at the decision feedback equalizer, which is used for to track the channel.

(iv) Channel Estimation Based on Comb-Type Pilot Arrangement:

Both LS and LMS estimators to estimate the channel at pilot frequencies has been used.The LMS estimator uses one tap LMS adaptive filter at each pilotfrequency. The first value is found directly through LS and the rest of the values are calculated based on the previous estimation and the current channel output as shown in fig. 4.

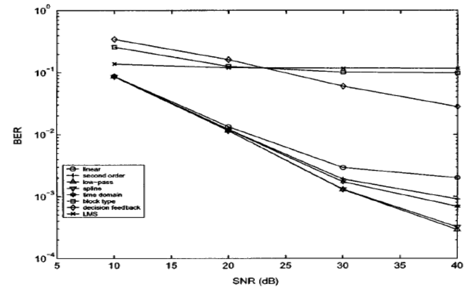

fig. 5: BPSK modulation with Rayleigh fading (channel 1, Doppler freq. 70 Hz).

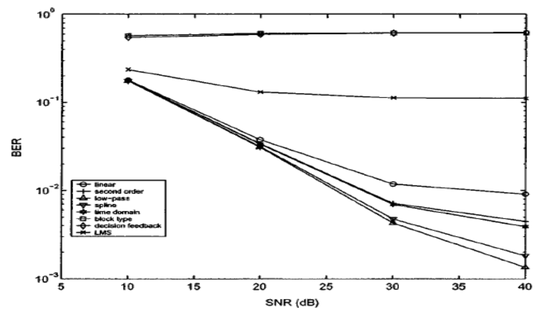

fig. 6: QPSK modulation with Rayleigh fading (channel 1, Doppler freq. 70 Hz).

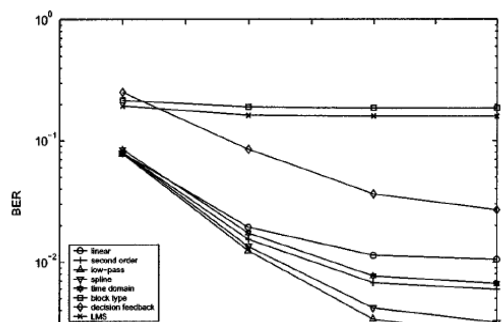

fig. 7: 16QAM modulation with Rayleigh fading (channel 1, Doppler freq.70 Hz).

The channel estimation at pilot frequencies is performed by using either LS or LMS. Then all of the possible interpolation techniques (linear interpolation, second order interpolation, low-pass interpolation, spline cubic interpolation, and time domain interpolation) areapplied to LS estimation results, to investigate the interpolation effects and linear interpolation is applied to LMS estimation results to compare with the LS overall estimation results.

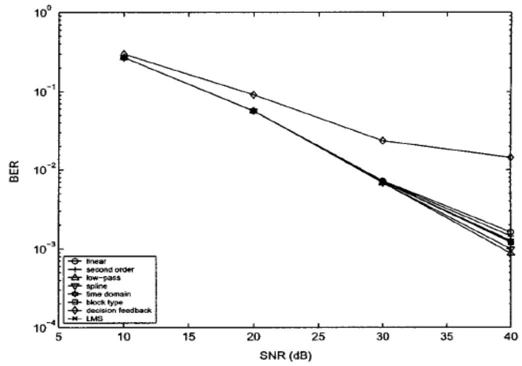

fig. 8: DQPSK modulation with Rayleigh fading (channel 1, Doppler freq.70 Hz).

B. Simulation Results

The words "linear, second-order, low-pass, spline, time domain" denotes the interpolation schemes of comb-type channel estimation with the LS estimate at the pilot frequencies, "block type" shows the block type pilot arrangement with LS estimate at the pilot frequencies and without adjustment, "decision feedback" means the block type pilot arrangement with LS estimate at the pilot frequencies and with decision feedback, and "LMS"is for the linear interpolation scheme for comb-type channel estimation with LMS estimate at the pilot frequencies.

Figs. 5–8 gives the BER performance of channel estimation algorithms for different modulations and for Rayleigh fading channel, with static channel response given in (8), Doppler frequency 70 Hz and OFDM parameters given in Table I. These results shows that the block-type estimation and decision feedback BER is 10–15 dB higher than that of the comb-type estimation type. This is because the channel transfer function changes so fast that there are even changes for adjacent OFDM symbols. The comb-type channel estimation with low pass interpolation achieves the best performance among all the estimation techniques for BPSK, QPSK, and 16QAM modulation. The performance among comb-type channel estimation techniques usually ranges from the best to the worst as follows: low-pass, spline, time-domain, second-order and linear. The results were expected since the low-pass interpolation used in simulation does the interpolation such that the mean-square error between the interpolated points and their ideal values isminimized. These results are also consistent with those obtained in [13] and [14].

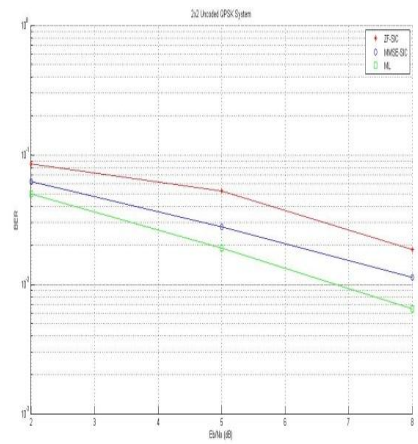

fig.9: 2x2 uncoded QPSK system

DQPSK modulation based channel estimation shows almost the same performance for all channel estimation techniques except the decision-feedback method. This is expected because dividing two consecutive data sub-carriers in signal de-mapper, eliminates the time varying fading channel effect. The error in estimation techniques result from the additive white noise. The BER performance of DQPSK for all estimation types is much better than those with modulations QPSK and 16QAM and worse than those with the BPSK modulation for high SNR.The general characteristics of the channel estimation techniques performs the same as fig. 7 for Rayleigh fading channel, whose static impulse response is given in Table II for 16QAM.

The general behavior of the plots is that BER increases as the Doppler spread increases. The reason is the existence of severe ICI caused by Doppler shifts. Another observation from this plot is that decision feedback block type channel estimation performs better than comb-type based channel estimation for low Doppler frequencies as suggested in [14] except low-pass and spline interpolation.It is alsao observed that time-domain interpolation performance is improved compared to other interpolation techniques as Doppler frequency increases.

5. Conclusion

In this paper, a full experimental study of block-type and comb-type pilot based channel estimation is done. Channel estimation based on comb-type pilot arrangement is presented by giving the channel estimation methods at the pilot frequencies and the interpolation of the channel at data frequencies. The simulation results shows that the comb-type pilot based channel estimation with low-pass interpolation performs the best among all channel estimation algorithms. This was expected since, the comb-type pilot arrangement allows the tracking of fast fading channel and low-pass interpolation does the interpolation such that the mean-square error between the interpolated points and their ideal values gets minimized. In addition, for low Doppler frequencies, the performance of decision feedback estimation is observed to be slightly worse than that of the best estimation. Therefore, some performance degradation can be tolerated for higher data bit rate for low Doppler spread channels although low-pass interpolation comb-type channel estimation is more robust for the increase in Doppler frequency.

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