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# Channel Estimation in OFDM Systems

**Anand Kumar, Ranjan Kumar**

Department of Electronics and Communication Engineering, Shri Ram College of Engineering and Management
Palwal, Haryana, India

## ABSTRACT

Orthogonal frequency division multiplexing (OFDM) provides an effective and low complexity means of eliminating intersymbol interference for transmission over frequency selective fading channels. This technique has received a lot of interest in mobile communication research as the radio channel is usually frequency selective and time variant. In OFDM system, modulation may be coherent or differential. Channel state information (CSI) is required for the OFDM receiver to perform coherent detection or diversity combining, if multiple transmit and receive antennas are deployed. In practice, CSI can be reliably estimated at the receiver by transmitting pilots along with data symbols. Pilot symbol assisted channel estimation is especially attractive for wireless links, where the channel is time-varying. When using differential modulation there is no need for a channel estimate but its performance is inferior to coherent system. In this thesis we investigate and compare various efficient pilot based channel estimati on schemes for OFDM systems. The channel estimation can be performed by either inserting pilot tones into all subcarriers of OFDM symbols with a specific period or inserting pilot tones into each OFDM symbol. In this present study, two major types of pilot arrangement such as block- type and comb-type pilot have been focused employing Least Square Error (LSE) and Minimum Mean Square Error (MMSE) channel estimators. Block type pilot sub-carriers is especially suitable for slow-fading radio channels whereas comb type pilots provide better resistance to fast fading channels. Also comb type pilot arrangement is sensitive to frequency selectivity when comparing to block type arrangement. The channel estimation algorithm based on comb type pilots is divided into pilot signal estimation and channel interpolation. The pilot signal estimation is based on LSE and MMSE criteria, together with channel interpolation using linear interpolation and spline cubic interpolation. The symbol error rate (SER) performances of OFDM system for both block type and comb type pilot subcarriers are presented in the work.

**Keywords:** Orthogonal frequency division multiplexing, Channel state information, Least Square Error , Minimum Mean Square Error , Advanced Mobile Phone Services

## I. INTRODUCTION

Radio transmission has allowed people to communicate without any physical connection for more than hundred years. When Marconi managed to demonstrate a technique for wireless telegraphy, more than a century ago, it was a major breakthrough and the start of a completely new industry. May be one could not call it a mobile wireless system, but there was no wire! Today, the progress in the semiconductor technology has made it possible, not to forgot affordable, for millions of people to communicate on the move all around the world.

The Mobile Communication Systems are often categorized as different generations depending on the services offered. The first generation comprises the analog frequency division multiple access (FDMA) systems such as the NMT and AMPS (Advanced Mobile Phone Services) [1]. The second generation consists of the first digital mobile communication systems such as the time division multiple access (TDMA) based GSM (Global System for Mobile Communication), D-AMPS (Digital AMPS), PDC and code division multiple access (CDMA) based systems such as IS-95. These systems mainly offer speech communication, but also data communication limited to rather low transmission rates. The third generation started operations on 1st October 2002 in Japan.

During the past few years, there has been an explosion in wireless technology. This growth has opened a new dimension to future wireless communications whose ultimate goal is to provide universal personal and multimedia communication without regard to mobility or location with high data rates. To achieve such an objective, the next generation personal communication networks will need to be support a wide range of services which will include high quality voice, data, facsimile, still pictures and streaming video. These future services are likely to include applications which require high transmission rates of several Megabits per seconds (Mbps).

In the current and future mobile communications systems, data transmission at high bit rates is essential for many services such as video, high quality audio and mobile integrated service digital network. When the data is transmitted at high bit rates, over mobile radio channels, the channel impulse response can extend over many symbol periods, which leads to inter symbol interference (ISI). Orthogonal Frequency Division Multiplexing (OFDM) is one of the promising candidate to mitigate the ISI. In an OFDM signal the bandwidth is divided into many narrow subchannels which are transmitted in parallel. Each subchannel is typically chosen narrow enough to eliminate the effect of delay spread. By combining OFDM with Turbo Coding and antenna diversity, the link budget and dispersive-fading limitations of the cellular mobile radio environment can be overcomed and the effects of co-channel interference can be reduced.

## II. METHODS AND MATERIAL

### 1. Literature Survey

The first OFDM scheme was proposed by Chang [2] in 1966 for dispersive fading channels, which has also undergone a dramatic evolution due to the efforts of [5]. Recently OFDM was selected as the high performance local area network transmission technique. A method to reduce the ISI is to increase the number of subcarriers by reducing the bandwidth of each subchannel hile keeping the total bandwidth constant .The ISI can instead be eliminated by adding a guard interval at the cost of power loss and bandwidth expansion. These OFDM systems have been employed in military applications since the 1960’s, for example by Bello [6], Zimmerman [7] and others. The employment of discrete Fourier transform (DFT) to replace the banks of sinusoidal generators and the demodulators was suggested by Weinstein and Ebert [5] in 1971, which significantly reduces the implementational complexity of OFDM modems. Hirosaki [8], suggested an equalization algorithm in order to suppress both intersymbol and intersubcarrier interference cau sed by the channel impulse response or timing and frequency errors. Simplified model implementations were studied by Peled [9] in 1980. Cimini [6] and Kelet [10] published analytical and early seminal experimental results on the performance of OFDM modems in mobile communication channels.

Most recent advances in OFDM transmission were presented in the impressive state of art collection of works edited by Fazel and Fettweis [11]. OFDM transmission over mobile communications channels can alleviate the problem of multipath propagation. Recent research efforts have focused on solving a set of inherent difficulties regarding OFDM, namely peak-to- mean power ratio, time and frequency synchronization, and on mitigating the effects of the frequency selective fading channels.

Channel estimation and equalization is an essential problem in OFDM system design. Basic task of equalizer is to compensate the influences of the channel [3]. This compensation requires, however, than an estimate of the channel response is available. Often the channel frequency response or impulse response is derived from training sequence or pilot symbols, but it is also possible to use nonpilot aided approaches like blind equalizer algorithms [12]. Channel estimation is one of the fundamental issues of OFDM system design, without it non coherent detection has to be used, which incurs performance loss of almost 3-4 dB compared to coherent detection [13]. If coherent OFDM system is adopted, channel estimation becomes a requirement and usually pilot tones are used for channel estimation. A popular class of coherent demodulation for a wide class of digital modulation schemes has been proposed by Moher and Lodge [14], and is known as Pilot Symbol Assisted Modulation, PSAM. The main idea of PSAM channel estimation is to multiplex known data streams with unknown data. Conventionally the receiver firstly obtain tentative channel estimates at the positions of the pilot symbols by means of remodulation and then compute final channel estimates by means of interpolation. Aghamohammadi [15] et al. and Cavers [16] were among the first analysing and optimizing PSAM given different interpolation filters. The main disadvantage of this scheme is the slight increase of the bandwidth. One class of such pilot symbol assisted estimation algorithms adopt an interpolation technique with fixed parameters (two dimensional and one dimensional) to estimate the frequency domain channel impulse response by using channel estimates obtained at the lattices assigned to the pilot tones. Linear, Spline and Gaussian filters have all been studied [17].

Channel estimation using superimposed pilot sequences is also a completely new area, idea for using superimposed pilot sequences has been proposed by various authors for different applications. In [18], superimposed pilot sequences are used for time and frequency synchronization. In [19], superimposed pilot sequences are introduced for the purpose of channel estimation, and main idea here is to linearly add a known pilot sequence to the transmitted data sequence and perform joint channel estimation and detection in the receiver. In [20], expectation maximization (EM) algorithm was proposed, and in [21] EM algorithm was applied on OFDM systems for efficient detection of transmitted data as well as for estimating the channel impulse response. Here, maximum likelihood estimate of channel was obtained by using channel statistics via the EM algorithm. In [22], performance of low complexity estimators based on DFT has been analysed. In [23], block and comb type pilot arrangements have been analysed.

There are some other techniques, proposed for channel estimation and calculation of channel transfer function in OFDM systems. For example, the use of correlation based estimators working in the time domain and channel estimation using singular value decomposition [24]. Its basically based on pilot symbols but in order to reduce its complexity, statistical properties of the channel are used in a different way. Basically the structure of OFDM allows a channel estimator to use both time and frequency correlations, but particularly it is too complex. In [24], they analysed a class of block oriented channel estimators for OFDM, where only the frequency correlation of the channel is used in estimation. Whatever, their level of performance, they suggested that they may be improved with the addition of second filter using the time correlation.

In [25], they proposed a channel estimation algorithm based polynomial approximations of the channel parameters both in time and frequency domains. This method exploits both the time and frequency correlations of the channel parameters. Use of the pilot symbols for channel estimation is basically an overhead of the system, and it is desirable to keep the number of pilot symbols to a minimum. In [26], Julia proposed a very good approach for OFDM symbol synchronization in which synchronization (correction of frequency offsets) is achieved simply by using pilot carriers already inserted for channel estimation, so no extra burden is added in the system for the correction of frequency offsets. Similarly in [27], it has been shown that the number of pilot symbols for a desired bit error rate and Doppler frequency is highly dependent on the pilot patterns used, so by choosing a suitable pilot pattern we can reduce the number of pilot symbols, but still retaining the same performance. Most common pilot patterns used in literature are block and comb pilot arrangements [23], [28]. Comb patterns perform much better than block patterns in fast varying environments [23].

## 2. Proposed Work

A wideband radio channel is normally frequency selective and time variant. For an OFDM mobile communication system, the channel transfer function at different subcarriers appears unequal in both frequency and time domains. Therefore, a dynamic estimation of the channel is necessary. Pilot-based approaches are widely used to estimate the channel properties and correct the received signal. In this chapter we have investigated two types of pilot arrangements.

The first kind of pilot arrangement shown in Figure3.1 is denoted as block-type pilot arrangement. The pilot signal assigned to a particular OFDM block, which is sent periodically in time-domain. This type of pilot arrangement is especially suitable for slow-fading radio channels. Because the training block contains all pilots, channel interpolation in frequency domain is not required. Therefore, this type of pilot arrangement is relatively insensitive to frequency selectivity. The second kind of pilot arrangement shown in Figure 3.2 is denoted as comb-type pilot arrangement. The pilot arrangements are uniformly distributed within each OFDM block. Assuming that the payloads of pilot arrangements are the same, the comb-type pilot arrangement has a higher re-transmission rate. Thus the comb-type pilot arrangement system is provides better resistance to fast-fading channels. Since only some sub-carriers contain the pilot signal, the channel response of non-pilot sub-carriers will be estimated by interpolating neighboring pilot sub-channels. Thus the comb-type pilot arrangement is sensitive to frequency selectivity when comparing to the block-type pilot arrangement system.

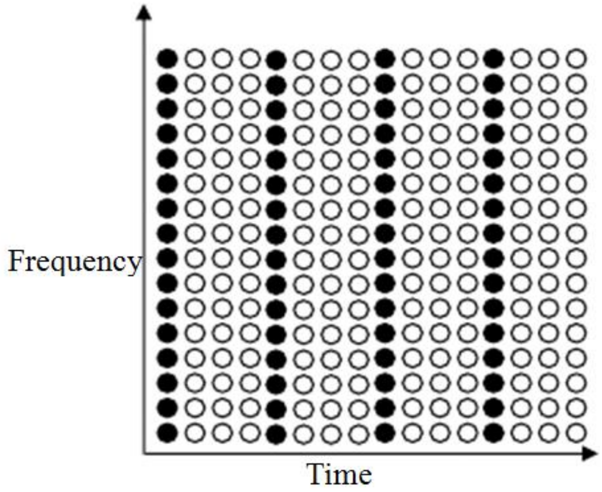

Figure. 3.1: Block type pilot arrangement

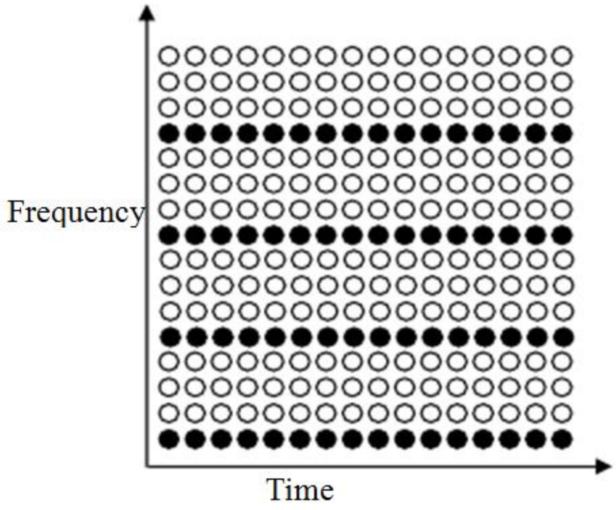

Figure. 3.2 : Comb type pilot arrangement

## 3. Channel Estimation Based On Block-Type Pilot Arrangement

In block-type pilot based channel estimation, OFDM channel estimation symbols are transmitted periodically, in which all sub-carriers are used as pilots. If the channel is constant during the block, there will be no channel estimation error since the pilots are sent at all carriers. The estimation can be performed by using either LSE or MMSE [23], [34].

If inter symbol interference is eliminated by the guard interval, we write (2.7) in matrix notation:

$$\begin{aligned} Y &= XFh + W \\ &= XH + W \end{aligned} \qquad 3.1$$

Where

$$\begin{aligned}
X &= diag\ \{X(0), X(1), \ldots\ldots X(N-1)\} \\
Y &= [Y(0), Y(1), \ldots\ldots Y(N-1)]^T \\
W &= [W(0), W(1), \ldots\ldots W(N-1)]^T \\
H &= [H(0), H(1), \ldots. H(N-1)]^T = DFT_N\{h\} \\
F &= \begin{bmatrix} W_N^{00} & \cdots & W_N^{0(N-1)} \\ \vdots & \ddots & \vdots \\ W_N^{(N-1)0} & \cdots & W_N^{(N-1)(N-1)} \end{bmatrix} \\
W_N^{nk} &= \frac{1}{N} e^{-j2\pi(n/N)k}
\end{aligned} \qquad 3.2$$

### 3.1. Minimum Mean Square Error (MMSE) Estimation:

$$\begin{aligned} J(e) &= E[(H - \hat{H})^2] \\ &= E[(H - \hat{H})^H (H - \hat{H})] \end{aligned} \qquad 3.3$$

MSE (mean square error)

Here $\hat{H} = MY$ where M is a linear estimator.

Invoking the wellknown orthogonality principle in order to minimize the mean square error vector $e = H - \hat{H}$ as to be set orthogonal by the MMSE equalizer to the estimators input vector

$$\begin{aligned} & E[(H - \hat{H})Y^H] = 0 \\ \Rightarrow\ & E[HY^H] - ME[YY^H] = 0 \\ \Rightarrow\ & E[FhY^H] - ME[YY^H] = 0 \end{aligned} \qquad 3.4$$

If the time domain channel vector h is Gaussian and uncorrelated with the channel noise W , then

$$FR_{hY} = MR_{YY} \qquad 3.5$$

Where $R_{hY} = E[hY^H]$ and $R_{YY} = E[YY^H]$

$$R_{hY} = E[hY^H] = E[h(XFh + w)^H]$$
$$R_{hY} = R_{hh}F^H X^H$$

because of $E[hw^H] = 0$ i.e. h is uncorrelated with w.

And
$$R_{YY} = E[YY^H] = E[(XFh + w)(XFh + w)^H]$$
$$R_{YY} = XFR_{hh}F^H X^H + \sigma^2 I_N \qquad 3.6$$

where $\sigma^2$ is the variance of noise.

$$M = FR_{hY}R_{YY}^{-1} \qquad 3.7$$
$$\hat{H} = FR_{hY}R_{YY}^{-1}Y \qquad 3.8$$

The time domain MMSE estimate of $h$ is given by

$$\hat{h}_{MMSE} = R_{hY}R_{YY}^{-1}Y \qquad 3.9$$

### 3.2 Least Square Error (LSE) Estimation:

We have to minimize.

$$J = (Y - XH)^H (Y - XH) \qquad 3.10$$
$$= (Y^T - H^H X^H)(Y - XH)$$
$$= Y^H Y - Y^H XH - H^H X^H Y + H^H X^H XH \qquad 3.11$$

For minimization of J we have to differentiate J with respect to H

$$\left.\frac{\partial J}{\partial H}\right|_{\hat{H}} = 0 \qquad 3.12$$

That is

$$-2Y^H X - 2\hat{H}^H X^H X = 0$$

$$\Rightarrow Y^H X = \hat{H}^H X^H X$$
$$\Rightarrow (Y^H X)(X^H X)^{-1} = \hat{H}^H (X^H X)(X^H X^{-1})$$
$$\Rightarrow Y^H XX^{-1}(X^H)^{-1} = \hat{H}^H$$
$$\Rightarrow Y^H (X^H)^{-1} = \hat{H}^H$$
$$\Rightarrow \hat{H} = [(X^H)^{-1}]^H Y$$
$$\Rightarrow \hat{H} = [(X^H)^{-1}]^H Y = X^{-1}Y$$
$$\Rightarrow \hat{H} = X^{-1}Y \qquad 3.13$$

The time domain LS estimate of $h$ is given by

$$\hat{h} = F^H X^{-1} Y \qquad 3.14$$

## III. RESULTS AND DISCUSSION

An OFDM system is modeled using Matlab to allow various parameters of the system to be varied and tested. The aim of doing the simulations is to measure the performance of OFDM system under different channel conditions, and to allow for different OFDM configurations to be tested.

### 4.1 OFDM Model Used In Simulations

An OFDM system model used is shown in Figure 4.1.

OFDM Transmitter

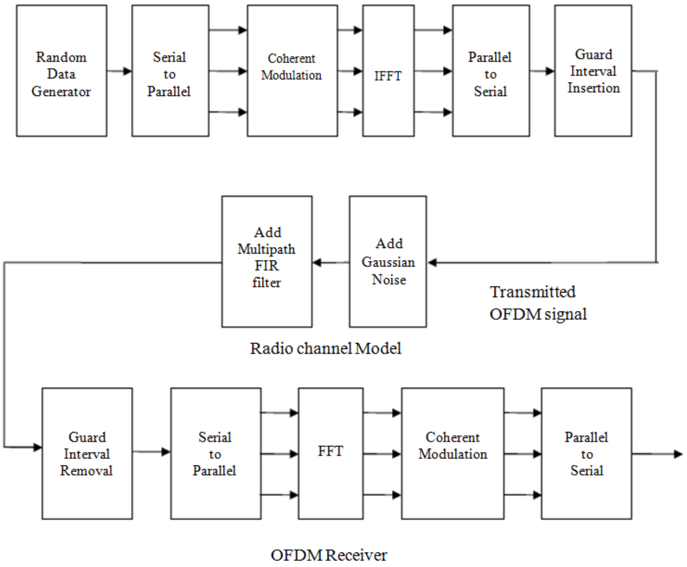

**Figure 4.1:** OFDM model used for Simulations

The input signal which we used is the random data generated by randn() function of the matlab, and limit the data to its maximum value e.g. 16 (for 16QAM).

SERIAL TO PARALLEL CONVERSION:

The input serial data stream is formatted into the word size required for transmission, e.g. 2bit/word for QPSK, and shifted into a parallel format. The data is then transmitted in parallel by assigning each data word to one carrier in the transmission.

MODULATION OF DATA

The data to be transmitted on each carrier is modulated into a QAM and M-ary PSK format. The data on each symbol is mapped. In the simulations we used 16-QAM BPSK,QPSK, 8 PSK modulation.

## INVERSE FOURIER TRANSFORM

After the required spectrum is worked out, an inverse fourier transform is used to find the corresponding time waveform. The guard period is then added to the start of each symbol.

## CHANNEL MODEL USED

A Channel model is then applied to the transmitted signal. Standard channel models used in mobile radio environment have been referred from [29],[35]. The model allows for the signal to noise ratio and multipath to be controlled. The signal to noise ratio is set by adding a known amount of white noise to the transmitted signal.

(1) In the block type pilot arrangement 16-QAM modulation scheme is used for a 64-subcarrier OFDM system with a two ray multipath channel. The channel impulse response h(t) is a time limited pulse train in the form of [29]

$$h(t) = \sum_{m} \alpha_m \delta(t - \tau_m T_s)$$

Where the amplitudes $\alpha_m$ are complex valued, $\tau_m$ is m th path delay and is sampling time. Guard time $T_G$is taken such that $0 \le \tau_m T_s \le T_G$.The above continuous time relationship can be represented as a discrete time version having discrete channel impulse response h(n) as:

$$h(n) = \sum_{m} \alpha_m e^{-j\frac{\pi}{N}(n+(N-1)\tau_m)} \frac{\sin(\pi \tau_m)}{\sin(\frac{\pi}{}(\tau_{m} - n))}$$

In the simulation for block type pilot arrangement we have taken two ray multipath channels.

$$h(t) = \delta(t - 0.5T_s) + \delta(t - 3.5T_s)$$

(2) In comb type pilot arrangement we have considered Rayleigh-fading channel. The frequency selective channel is assumed to be Rayleigh-fading, with channel impulse response $h(l) = [h(0),........h(L-1)]^T$ where L=40 is the number of taps are uncorrelated complex Gaussian random variables with zero mean[35]. We adopt an exponential power profile delay for taps.

**Receiver**

The receiver basically does the reverse operation to the transmitter. The guard period is removed. The FFT of each symbol is then taken to find the original transmitted spectrum. Each transmission carrier is then evaluated and converted back to the data word by demodulating the received symbol. The data words are then combined back to the same word size as the original data.

### 4.2 Simulation Result for Block Type Pilot Arrangement

In the simulation we consider a system operating with a bandwidth of 500 kHz, divided into 64 tones with total symbol period of 138 s, of which 10 s is a cyclic prefix. Sampling is performed with a 500 kHz rate. A symbol thus consists of 69 samples, five of which are contained in the cyclic prefix. 10,000 channels are randomized per average SNR. We consider the two ray channel as h(t) □ □ (t − 0.5Ts ) □ □ (t − 3.5Ts ) [29]. Figure 5.2 demonstrates discrete time impulse response |h(n)| at different taps. Figure 5.3 demonstrates Mean square error of channel estimation at different SNRs in dB. As SNR increases mean square error decreases for both LSE and MMSE. Figure 5.4 shows Average SNR versus Symbol Error Rate (SER). As SNR increases Symbol Error Rate decreases for both cases. For a given SNR, MMSE estimator shows better performance than LSE estimator. The complexity of MMSE estimators will be larger than LSE estimators but give better performance in comparison to LSE. It should be noticed that MMSE estimator have been derived under assumption of known channel correlation and noise variance. In practice these quantities Rhh and □ n , are either taken as fixed or estimated, possibly in an adaptive way. This will increase the estimator complexity but improve performance over LSE estimators.

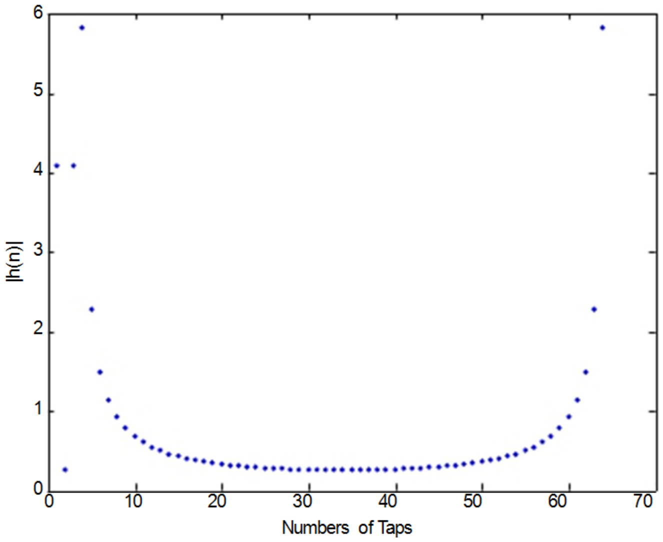

**Figure 4.2:** Channel impulse response |h(n)|

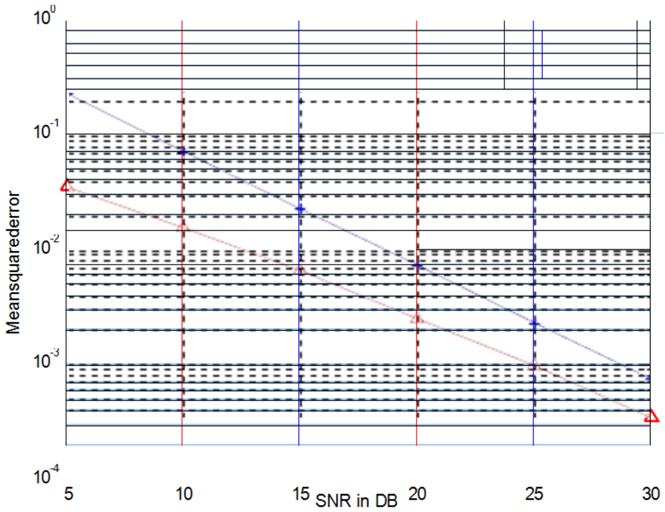

**Figure 4.3:** Mean-Square Error for LSE and MMSE estimators at different SNRs.

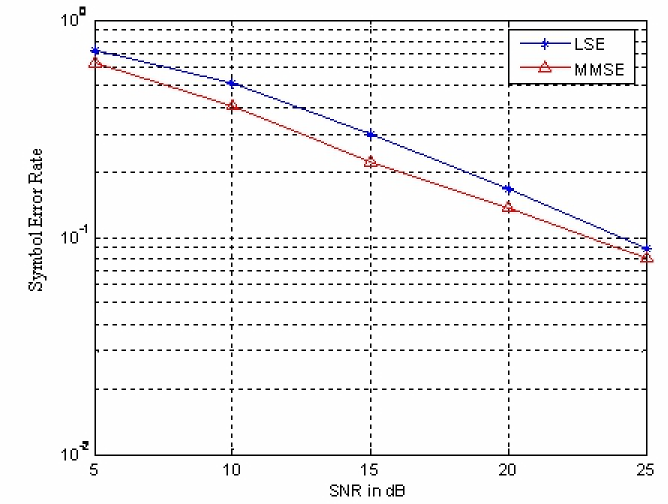

**Figure 4.4:** SER for LSE and MMSE estimators at different SNRs

## 4.3 Simulation Result for Comb-Type Pilot Arrangement:

For comb type pilot arrangement we consider an OFDM system with N=1024 subcarriers. The frequency selective Rayleigh channel has L= 40 zero-mean uncorrelated complex Gaussian random taps.

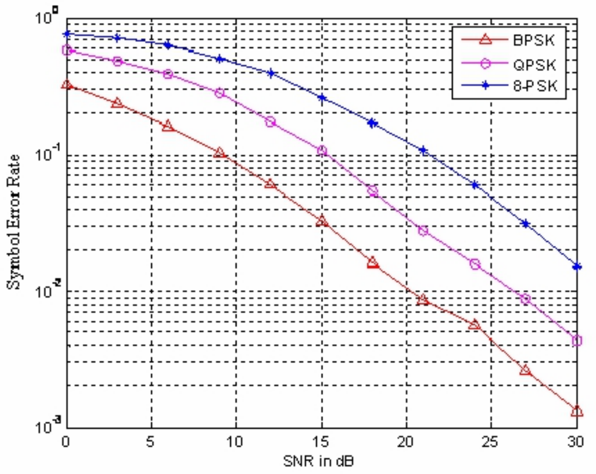

**Figure 4.5:** SER (MMSE channel Estimation) for M-PSK modulation for different SNRs

The spacing between pilots are taken as 4. So the number of pilots are 256 and number of information symbols are 768. In the simulation we consider BPSK, QPSK and 8-PSK modulations. Figure 5.5 and Figure 5.6 demonstrate Symbol Error Rate (SER) performance (SNR versus SER) for different modulations in MMSE and LSE estimators respectively. It shows that as SNR increases the Symbol error rate decreases and also by going higher order modulation Symbol Error Rate increases which is coming true as we expected.

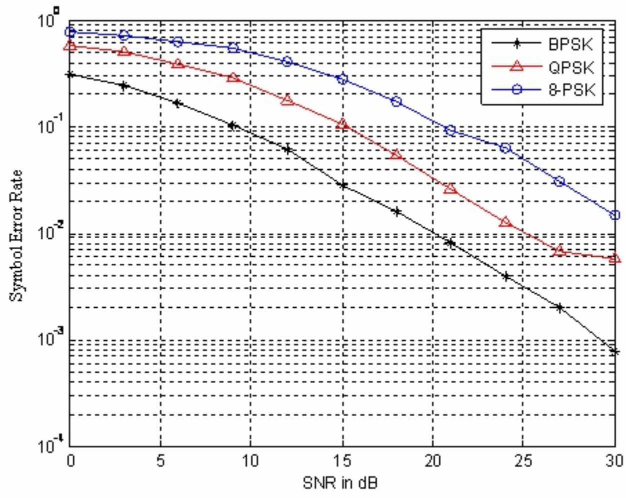

**Figure 4.6:** Bit Error rate versus SNR (LSE channel Estimation) for M-PSK modulation

In Figure 4.7 we compared the performance between MMSE and LSE estimators. MMSE estimators have less Symbol Error Rate than LSE estimators in low SNRs. But at higher SNRs both will have equal performance. At lower SNRs noise is the prominent factor. In this case MMSE estimator works better. But at higher SNRs, it is better to go for LSE estimator because of its simplicity where noise is less effective. Figure 5.8 shows result for interpolation techniques used in the simulation. The interpolation techniques are applied to LSE estimation. It is foundthat spline interpolation having better performance than linear interpolation.

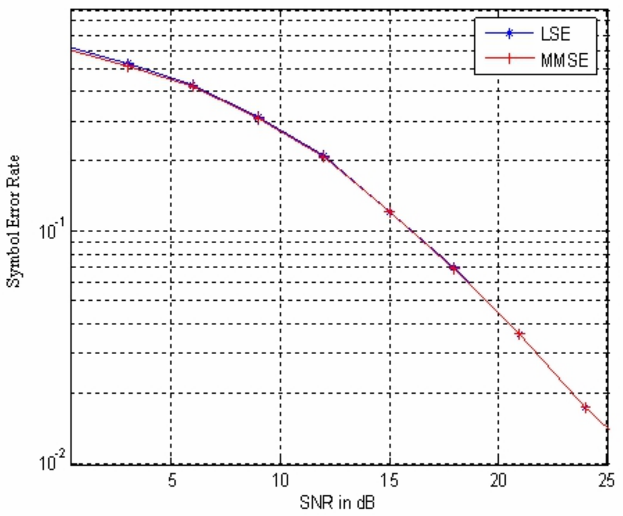

**Figure 4.7:** SER comparison between LSE and MMSE channel estimation

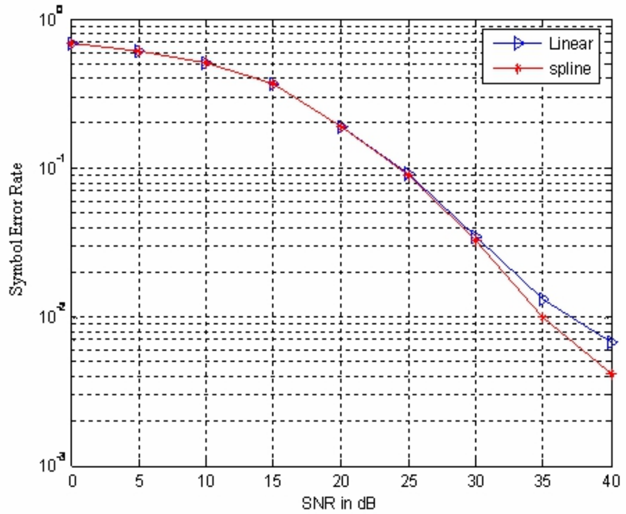

**Figure 4.8:** BER comparison between Linear and Spline interpolations

Figure 4.9 and Figure4.10 demonstrate the Mean square error versus Number of pilots for MMSE and LSE estimators respectively. As number of pilots increases mean square error decreases. With the increase in number of pilots, MSE reduces and achieves the lower limit. So increasing the number of pilots beyond certain limit becomes unnecessary. Further sending more number of pilots results decrease in number of information symbols and redundant pilots can be eliminated.

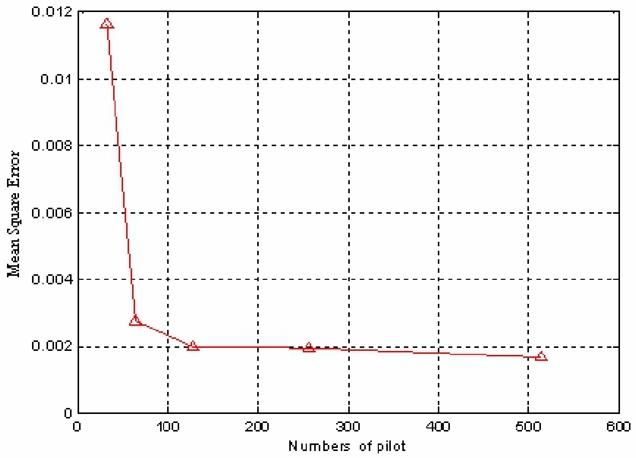

**Figure 4.9:** Mean Square Error versus Number of pilots (MMSE estimation)

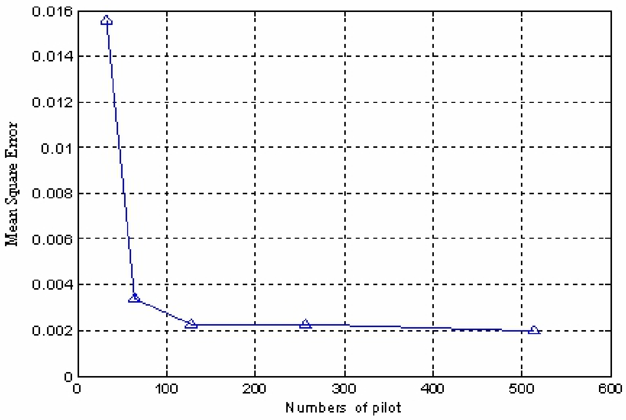

**Figure 4.10:** Mean Square Error versus Number of pilots (LSE estimation)

## IV. CONCLUSION

In this work, we have studied LSE and MMSE estimators for both block type and comb type pilot arrangement. The estimators in this study can be used to efficiently estimate the channel in an OFDM system given certain knowledge about channel statistics. The MMSE estimators assume a priori knowledge of noise variance and channel covariance. Moreover, its complexity is large compare to the LSE estimator. For high SNRs the LSE estimator is both simple and adequate. The MMSE estimator has good performance but high complexity. The LSE estimator has low complexity, but its performance is not as good as that MMSE estimator basically at low SNRs.

In comparison between block and comb type pilot arrangement, block type of pilot arrangement is suitable to use for slow fading channel where channel impulse response is not changing very fast. So that the channel estimated, in one block of OFDM symbols through pilot carriers can be used in next block for recovery the data which are degraded by the channel. In our simulation of block type pilot arrangement we used two ray static channels for 16-QAM modulation. Here 64 numbers of carriers are used in one OFDM block. We calculated BER and MSE in channel estimation for different SNRs in simulation. Comb type pilot arrangement is suitable to use for fast fading channel where the channel impulse response is changing very fast even if one OFDM block. So comb type of pilot arrangement cannot be used in this case. We used both data and pilot carriers in one block of OFDM symbols. Pilot carriers are used to estimate the channel impulse response. The estimated channel can be used to get back the data sent by transmitter certainly with some error. In the simulation we used 1024 number of carriers in one OFDM block. In which one fourth are used for pilot carriers and rest are of data carriers. We calculated BER for different SNR conditions for M-PSK signalling. We also have compared performance of LSE with MMSE estimator. MMSE estimation is better that LSE estimator in low SNRs where at high SNRs performance of LSE estimator approaches to MMSE estimator. We also used interpolation techniques for channel estimation. It is found that higher order interpolation technique (spline) is giving better performance than lower order interpolation technique (linear). In simulation we have also calculated MSE for estimation of channel with number of pilot arrangement. MSE decreases when number of pilots increase. But we have to limit the number pilots when mean square error comes constant.

## V. FUTURE WORK

Following are the areas of future study which should be considered for further research work.

1. Implementation of other interpolation techniques for channel estimation: In this work we have considered only two type interpolation techniques. We can extend this work for other interpolation techniques such as second order, low-pass etc.
2. Feasibility study of Multiple Input Multiple Output (MIMO) OFDM systems: In this study we have discussed about Single Input Single Output (SISO) OFDM systems. MIMO OFDM can be implemented using multiple transmitting and receiving antennas which is an interesting work of future.

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