A Comb-Type Pilot Symbol Aided Channel Estimation for STBC based OFDM System over Frequency Selective Channel

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Abstract— **In this paper, the channel estimation technique for space time block code (STBC) based multi-input multi-output (MIMO) orthogonal frequency division multiplexing (OFDM) is investigated for multipath fading channel. The channel estimation is based on the comb-type pilot arrangement where the pilot subcarriers are placed at regular interval of each OFDM symbol block and are orthogonal between different transmitting antennas. Due to the advantages of orthogonal pilot subcarrier, the original transmitted signal is completely recovered from the mixed transmitted signal at the receiver side. The least square (LS) algorithm is adopted for estimation of channel at pilot subcarrier while the interpolation is done at data subcarrier. The performance of the developed channel estimation technique is compared with the traditional single-input single-output (SISO) OFDM system on the basis of symbol error rate (SER). The simulation results show that the STBC OFDM gives better performance than SISO OFDM and the SER decreases as the signal to noise ratio (SNR) and the number of receive antenna increases.**

Keywords — **OFDM, STBC, Pilot Subcarrier, Interpolation, Channel Estimation**

I. INTRODUCTION

Now a days, the wireless communication system is more focused on reliability and spectral efficiency [1]-[2]. The link reliability is solved by STBC technique which is proposed by Alamouti [3]. The STBC technique is expanded to arbitrary number of transmit and receive antenna in [4]-[5]. Originally, the STBC technique is applied to flat fading channel and it is assumed that the complete channel knowledge is known at the receiver. But in practical scenario, the channel is frequency selective fading rather than flat fading and the channel knowledge is unknown to the receiver. This problem can be solved by applying OFDM technique to the STBC system as OFDM converts the frequency selective fading channel into many narrow parallel flat fading channels [6]. The other important property of OFDM is the spectral efficiency due to the orthogonality between the subcarriers. Thus, applying the STBC technique to the OFDM system can provide high data rate, reliability between links and high spectral efficiency. However, in such systems, the channel state information (CSI) is required to be known at the receiver side in order to recover the transmitted signal. There are two approaches for channel estimation namely the blind channel estimation and pilot aided channel estimation. In blind channel estimation, the statistical properties of the received signal are required to recover the transmitted signal. Such system has high spectral efficiency as no pilot symbol is used for channel estimation. In case of pilot aided channel estimation, pilot symbols are known a prior to the receiver and are multiplexed with the transmitted data streams for channel estimation. As compared to pilot aided channel estimation, the blind channel estimation is limited to slow time varying channel, has higher complexity and poorer performance. Hence, in this paper, pilot aided channel estimation is carried out for channel estimation purpose.

In the previous literature, many techniques have been developed for channel estimation of OFDM system [7]-[9]. In [9], a comparison of channel estimation has been presented based on different modulation schemes and interpolation techniques. Pilot aided channel estimation [10]-[12] has been proposed based on least square (LS) and minimum mean squared error (MMSE) algorithms for MIMO OFDM systems. For STBC OFDM systems, orthogonal pilot symbols are inserted at the transmitter and used at the receiver to know the CSI [13]-[15]. But in these papers, the detail description of the recovery of the transmitted signal based on orthogonal pilot subcarrier was absent. The detail analysis of the orthogonal pilot symbols is described in the paper [16]. In [12], the difference between the nonzero-form and zero-form of pilot structure was investigated and it is verified that these two techniques have similar performance. Hence, nonzero-form of pilot arrangement is applied in this paper. . Another important criterion of channel estimation is the interpolation techniques. Linear, spline, second order, low pass interpolation methods have been investigated in [9] and demonstrated that pilot aided channel estimation based on low pass interpolation gives the best performance among all the interpolation technique.

In this paper, the channel estimation is done by using LS algorithm with nonzero-form of comb type orthogonal pilot structure at pilot subcarrier while the low pass interpolation method is applied at data subcarrier for STBC based MIMO OFDM over IEEE 802.11 channel.

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The rest of the paper is organized as follows. In section II, the system model for the STBC based OFDM system along with the channel model is discussed. The channel estimation technique is presented in Section III. In section IV, the computer simulation is carried out for IEEE 802.11 model and the performance of the developed channel estimation is analyzed. Finally, Section V concludes the paper.

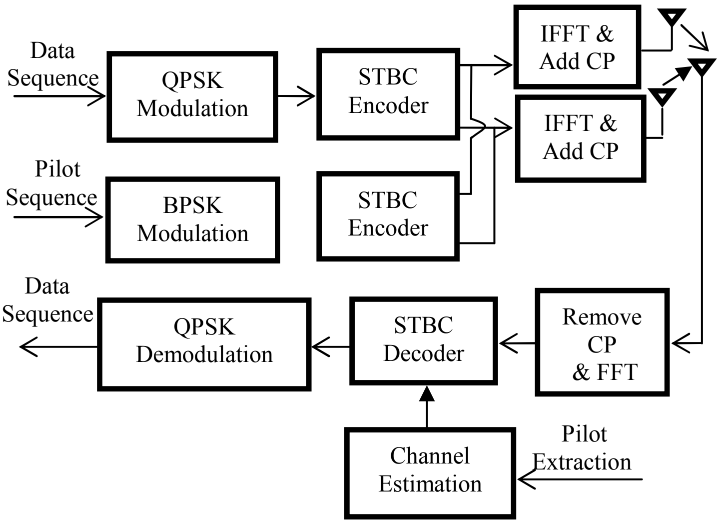

Figure 1 Block diagram of an STBC-OFDM system model

II. SYSTEM MODEL

In this section, an STBC based OFDM system with two transmit antenna and N_r number of receive antennas is described along with the IEEE 802.11 channel model as multipath Rayleigh fading channel.

A. STBC BASED OFDM SYSTEM MODEL

The system model for STBC-OFDM with two transmit antenna and one receive antenna is shown in the Figure1. However, the system model can be extended to any number of transmit and receive antennas to obtain higher transmit diversity. At the transmitter side, the data sequence is generated and modulated according to any specific modulation scheme such as BPSK, QPSK or 16QAM. Then the output modulated data are passed through the STBC encoder. The STBC encoder converts the single input modulated information data into two parallel encoded output data according to Alamouti STBC scheme [3]. The pilot sequence is also generated and modulated similar to the data sequence. Then both the encoded data and pilot subcarrier are passed through the serial to parallel converter(S/P) and finally reached at the Inverse Fast Fourier Transformation (IFFT) block.

The output of the IFFT block can be expressed as

$$x^{\beta}_{t,n} = \sum_{k=0}^{N-1} X^{\beta}_{t,k}\, e^{j2\pi kn/N} \tag{1}$$

$$\beta = 1,2, \quad n, k = 0,1,2,.......N-1$$

where

$X^{\beta}_{t,k}$, $x^{\beta}_{t,n}$ denotes data vector before and after of the IFFT block, β denotes the transmit antenna index, and n, k represents the k^{th} subcarrier and the corresponding n^{th} time instant at the t^{th} symbol period . N denotes the total number of OFDM data subcarrier.

Finally, the resulting signals are transmitted from the antennas after insertion of the cyclic prefix (CP) which is assumed to be larger than delay spread of the multipath channel in order to avoid inter symbol interferences (ISI).The channel is assumed to be static or quasi-static for the two time slot of the STBC block . The channel model used in this paper is described latter in this section.

The received signal can be obtained by taking the convolution of transmitted data signal with the channel impulse response and can be expressed as

$$r_{j,t,n} = \sum_{l=0}^{L-1} h^{\beta}_{j,t,l} x^{\beta}_{t,n-l} + w_{j,t,n} \tag{2}$$

where

$h^{\beta}_{j,t,l}$ is the channel impulse response of the l^{th} path at t^{th} time slot for β^{th} transmit antenna and j^{th} receive antenna in time domain.

At the receiver side, at first the CP is removed and then the received signal is processed by a Fast Fourier Transformation (FFT). The FFT output of the received signal after the removal of CP can be written as

$$R_{j,t,k} = \sum_{\beta=1}^{N_t} H^{\beta}_{j,t,k} X^{\beta}_{t,k} + W_{j,t,k} \tag{3}$$

where $H^{\beta}_{j,t,k} = \sum_{k=0}^{N-1} h^{\beta}_{j,t,l} e^{-j2\pi 2\pi/N}$

and $j = 1,2,....N_r, \quad \beta = 1,2.$

$H^{\beta}_{j,t,k}$ is the frequency response of the channel from β^{th} transmit antenna to the j^{th} receive antenna and on the k^{th} subcarrier. N_t and N_r represents the number of transmit and receive antennas. $W_{j,t,k}$ is the additive white Gaussian noise with zero mean and unit variance.

Then the processed signal is decoded by the STBC decoding scheme. Finally, the transmitted signal is recovered after taking the hard decision of the decoded signal.

B. CHANNEL MODEL

In this paper, IEEE802.11 model with an exponential power delay profile (PDP) is adopted. The channel is modeled as finite impulse response (FIR) with total $L+1$ non-zero path with zero mean and average power of σ_l^2. The channel can be expressed by

$$h_l = N(0,\frac{\sigma_l}{2}) + jN(0,\frac{\sigma_l}{2}) \qquad (4)$$

where $N(0,\frac{\sigma_l}{2})$ is the zero mean with variance σ_l^2.

The power of multipath component decreases exponentially. The first path of the model is chosen to be

$$\sigma_0^2 = \frac{1-\lambda}{1-\lambda^{L+1}} \qquad (5)$$

where $\lambda = e^{\frac{T_s}{\tau_{rms}}}$ and $L = \frac{10\,\tau_{rms}}{T_s}$

The T_s and τ_{rms} are the sampling period and root mean squared delay of the channel respectively. The energy of the l^{th} path can be written as

$$\sigma_l^2 = \sigma_0^2 \lambda^l \qquad (6)$$

III. CHANNEL ESTIMATION

In order to estimate the channel based on pilot blocks for MIMO OFDM system, some modification must be considered for better estimation purpose [16] which are given below

(1) The total number pilot used should be equal to the number of pilot used for SISO OFDM system multiplied by the number of transmitting antennas. Hence, the numbers of pilots are increased as the number of transmitting antennas increased.
(2) The pilot blocks transmitted on different antennas must be orthogonal to each other in order to recover the transmitted signal completely from the mixed up transmitted signal at the receiver side.
(3) Besides the above two properties, the inter-transmitter-antennas-interference (ITAI) must be avoided for better channel estimation. The ITAI effect is completely removed by orthogonal pilot structure and is discussed below.

There are two types of pilot arrangement for orthogonal pilot subcarrier namely nonzero-form pilot and zero-form pilot. In nonzero-form pilot pattern, both the transmitting antennas send the signal simultaneously. In other case, for zero-form pilot arrangement, when one antenna is transmitting the pilot block, the other antenna must be kept silent and vice-versa. Hence, in zero-form pilot, the ITAI is avoided. But the disadvantage is that less channel frequency response (CFR) is acquired because half of the time no estimation is performed. As suggested in [12], the performance is same for both the type of pilot arrangement. Hence in this paper, the nonzero-form pilot pattern is employed.

In comb type pilot based channel estimation, the total $2Np$ pilot subcarriers are uniformly inserted into the two consecutive OFDM symbols. For easy understanding, two successive OFDM blocks are taken at a time and is given by

$$X_{2k}^{\beta} = X^{\beta}_{(2kpL+l)} = \left\{ \begin{array}{ll} P_{2kp}^{\beta} & l = 0 \\ P_{2kp+1}^{\beta} & l = 1 \\ S_{2ks}^{\beta} & l = 2,....L-1 \end{array} \right\} \qquad (7)$$

where

$L = Total\ \ number\ \ of\ \ subcarriers\ /\ Np$.

$2kp = 0,1,.....2Np - 1$, $2\mathrm{ks} = 0,1,.......2\mathrm{Ns} - 1$, $2\mathrm{k} = 0,1,......2\mathrm{N} - 1$

P_{2kp}^{β} , P_{2kp+1}^{β} denote the $2kp$ and $2kp+1^{\text{th}}$ pilot subcarrier value respectively and S_{2ks}^{β} denotes the data subcarrier excluding the pilot subcarrier value. Np and N represents the total number of pilot and data subcarrier in a single OFDM system respectively. The total number of available data subcarrier except the number of pilot subcarrier is denoted by N_s.

After the insertion of pilot subcarrier into the data subcarrier, the encoded pilot and data subcarrier for two consecutive OFDM symbol block can be written as

$$\begin{aligned} X_{2k}^{1} &= [p_{1,} - p_2^*, s_1, - s_2^*, ..., s_{2Ns-1}, -s_{2Ns}^*] \\ X_{2k}^{2} &= [p_{2,} p_1^*, s_2, s_1^*, ..., s_{2Ns}, s_{2Ns-1}^*] \\ P_{2k_P}^{1} &= [p_{1,} - p_2^*, ..., p_{2Np-1}, -p_{2Np}^*] \\ P_{2k_P}^{2} &= [p_{2,} p_1^*, ..., p_{2Np}, p_{2Np-1}^*] \end{aligned} \qquad (8)$$

where

$X_{2k}^{\beta}, P_{2kp}^{\beta}$ denotes the data and pilot subcarrier value for $2k^{th}$ and $2k_p^{th}$ subcarrier respectively for transmitting antenna $\beta =$ 1,2 before the IFFT operation. ‘*’ denotes complex conjugate operation.

Actually, the data and pilot subcarrier are transmitted from two different transmitting antennas in two different time slot and can be expressed as

$$
\begin{aligned}
X^{1}_{t,k} &= [p_1, s_1, \ldots\ldots\ldots\ldots, s_{2Ns-1}] \\
X^{2}_{t,k} &= [p_2, s_2, \ldots\ldots\ldots\ldots\ldots, s_{2Ns}] \\
X^{1}_{t+T,k} &= [-p_2^{*}, -s_2^{*}, \ldots\ldots\ldots, -s_{2Ns}^{*}] \\
X^{2}_{t+T,k} &= [p_1^{*}, s_1^{*}, \ldots\ldots\ldots\ldots, s_{2Ns-1}^{*}] \\
P^{1}_{t,k_P} &= [p_1, p_3 \ldots\ldots\ldots\ldots, p_{2Np-1}] \\
P^{2}_{t,k_P} &= [p_2, p_4 \ldots\ldots\ldots\ldots\ldots, p_{2Np}] \\
P^{1}_{t+T,k_P} &= [-p_2^{*}, -p_4^{*} \ldots\ldots, -p_{2Np}^{*}] \\
P^{2}_{t+T,k_P} &= [p_1^{*}, p_3^{*} \ldots\ldots\ldots\ldots, p_{2Np-1}^{*}]
\end{aligned}
\tag{9}
$$

where $X^{\beta}_{t,k}$ and $X^{\beta}_{t+T,k}$ are the k^{th} data subcarrier value for t^{th} and $t+T^{th}$ time slot respectively.

The orthogonal properties of the pilot subcarrier can be verified by some simple mathematics which is given below

$$
\begin{aligned}
P^{1}_{t,k_P} \times \left(P^{2}_{t,k_P}\right)^{*} + P^{1}_{t+T,k_P} \times \left(P^{2}_{t+T,k_P}\right)^{*} &= 0 \\
\left(P^{1}_{t,k_P}\right)^{*} \times P^{2}_{t,k_P} + \left(P^{1}_{t+T,k_P}\right)^{*} \times P^{2}_{t+T,k_P} &= 0
\end{aligned}
\tag{10}
$$

Hence, from the equation (10), it can be seen that the result is always zero if the two transmitting antennas operates cross-wise with each other.

After the addition of the CP, the signal is send through the channel. According to STBC scheme [3], the channel is assumed to be constant for two different time slot of the same transmitting, hence the channel can be written as

$$
H^{\beta}_{t,k} = H^{\beta}_{t+T,k} \tag{11}
$$

where $H^{\beta}_{t,k}$ denotes the frequency response of the channel at k^{th} subcarrier for t^{th} time slot and for the β^{th} transmitting antenna.

At the receiver side, the signal is first processed by an FFT operation and then the pilot subcarriers are extracted in order to estimate the channel at pilot positions. The received data and pilot subcarrier for t^{th} and $t+T^{th}$ time slots are denoted by $Rp_{t,k}$, $Rp_{t+T,k}$ and $Rp_{t,kp}$, $Rp_{t+T,kp}$ respectively and are given by equation (12) and (13).

$$
\begin{aligned}
Rp_{t,k} &= H^{1}_{t,k} X^{1}_{t,k} + H^{2}_{t,k} X^{2}_{t,k} + W_{t,k} \\
Rp_{t+T,k} &= -H^{1}_{t,k} X^{2\,*}_{t,k} + H^{2}_{t,k} X^{1\,*}_{t,s} + W_{t+T,k}
\end{aligned}
\tag{12}
$$

$$
\begin{aligned}
Rp_{t,kp} &= H^{1}_{t,kp} P^{1}_{t,kp} + H^{2}_{t,kp} P^{2}_{t,kp} + W_{t,kp} \\
Rp_{t+T,kp} &= -H^{1}_{t,kp} P^{2\,*}_{t,kp} + H^{2}_{t,kp} P^{1\,*}_{t,kp} + W_{t+T,kp}
\end{aligned}
\tag{13}
$$

For the time being, it is assumed that the complete CSI is known at the receiver. The decoded signal can be obtained by applying STBC decoding scheme to the received signal at data subcarrier and is given by the equation (14).

$$
\begin{aligned}
\tilde{X}^{1}_{t,k} &= H^{1\,*}_{t,k} Rp_{t,k} + H^{2}_{t,k} Rp_{t+T,k}^{*} \\
\tilde{X}^{2}_{t,k} &= H^{2\,*}_{t,k} Rp_{t,k} - H^{1}_{t,k} Rp_{t+T,k}^{*}
\end{aligned}
\tag{14}
$$

Finally, the original data subcarrier can be obtained by applying hard decision in the equation (14) and is given by

$$
\begin{aligned}
\hat{X}^{1}_{t,k} &= Q(\tilde{X}^{1}_{t,k}) \\
\hat{X}^{2}_{t,k} &= Q(\tilde{X}^{2}_{t,k})
\end{aligned}
\tag{15}
$$

where

Q denotes the hard decision function.

But, unfortunately the channel is not known to the receiver, hence, to get the channel knowledge at the receiver side, the channel estimation has been applied. The LS estimation algorithm is applied to estimate the channel at pilot subcarrier because it is the simplest technique and due to orthogonal properties of pilot subcarrier between the different transmitting antennas, no matrix inversion is required.

The developed equations for channel estimation can be obtained after some simple mathematical modification to the equation (13) and is given by

$$
\begin{aligned}
\hat{H}^{1}_{t,kp} &= \frac{Rp_{t,kp} P^{1\,*}_{t,kp} - P^{2}_{t,kp} Rp_{t+T,kp}}{\left|P^{1}_{t,kp}\right|^{2} + \left|P^{2}_{t,kp}\right|^{2}} \\
\hat{H}^{2}_{t,kp} &= \frac{Rp_{t,kp} P^{2\,*}_{t,kp} + P^{1}_{t,kp} Rp_{t+T,kp}}{\left|P^{1}_{t,kp}\right|^{2} + \left|P^{2}_{t,kp}\right|^{2}}
\end{aligned}
\tag{16}
$$

where

$Rp_{t,kp}$, $P_{t,kp}$ are the output and input pilot subcarrier value respectively and $\hat{H}^{1}_{t,kp}$, $\hat{H}^{2}_{t,kp}$ are the CFR at pilot subcarrier for first and second path respectively.

In order to estimate the channel at data subcarrier by using channel information at pilot subcarrier, the interpolation technique is needed. This paper uses two type of interpolation technique namely spline and low-pass type interpolation technique. The spline type interpolation produces a smooth and continuous polynomial fitted to original data sequence.

The low-pass interpolation can be obtained by inserting zero into the original data sequence and then applying a low-pass FIR filter in such a way that the mean square error between ideal and interpolated values is minimum [9].The estimated channel at data subcarrier can be applied to the equation (14) to get the decoded data signal. Finally, the decoded data signal is applied in the equation (15) in order to completely recover the original transmitted data sequence from the mixed transmitted data signals at the receiver side. Since the matrix inversion is not required, this method is very simple and cost effective while achieving accurate channel estimation.

IV. SIMULATION RESULTS

In this section, the channel estimation performance is evaluated for conventional SISO OFDM and the STBC based OFDM for multipath fading channel based on SER. The channel is chosen to be IEEE 802.11 model based exponential power delay profile. The total simulation parameter used for simulation is listed on the Table1.The LS algorithm is used for channel estimation purpose with spline and low-pass interpolation technique in order to investigate the interpolation effect. The QPSK and 16QAM modulation is applied to data subcarrier whereas BPSK modulation is applied to the pilot subcarrier to achieve better estimation.

Table1. Simulation Parameter

Parameter	Value
FFT Size	128
Number of Subcarrier	128
Number of used subcarrier	112
Number of CP	16
Number of Pilot subcarrier	16
Pilot Type	Comb-Type
Data Modulation	QPSK/16QAM
Pilot Modulation	BPSK
Channel BW	10MHz
Subcarrier Spacing	78.125KHz
Channel Model	IEEE 802.11
RMS Delay	50ns
Excess Delay	500ns

The SER performance for QPSK modulated data subcarrier with different interpolation technique for SISO OFDM, STBC OFDM with two transmit antenna and one receive antenna and STBC OFDM with two transmit antenna and two receive antenna is shown in the Figure 2. It can be seen that the STBC based OFDM system outperforms the simple OFDM system. In Figure3, the 16QAM modulation technique is applied to OFDM and STBC-OFDM for comparison of modulation effect on data subcarrier. We can see that 16QAM perform worse than QPSK modulation although it provides higher data rate than QPSK modulation. The low-pass interpolation gives better performance than spline type interpolation as shown in the Figure 2 and Figure 3. Further, we can see that SER value decreases as the SNR value and number of receive antenna increases. Finally, the Figure 2 and Figure 3 show that the developed channel estimation has a loss between 2 to 2.5dB SNR than that of the ideal case where it is assumed that the complete channel knowledge is known at the receiver side.

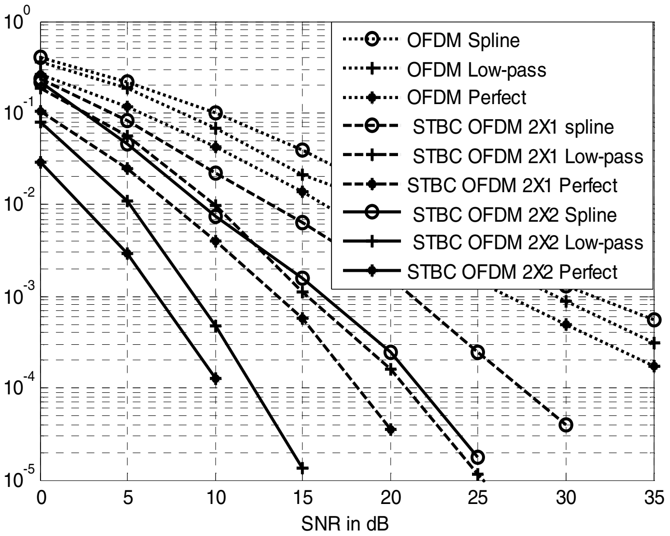

Figure 2 SER versus SNR for QPSK modulated OFDM and STBC based OFDM over Frequency selective Rayleigh channel

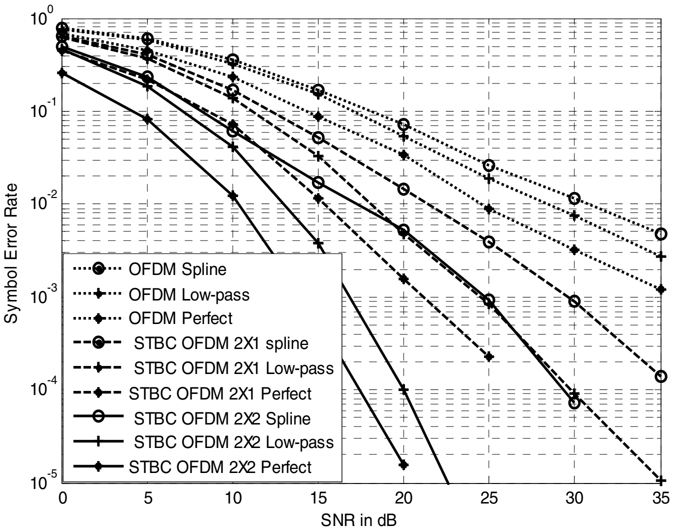

Figure 3 SER versus SNR for 16-QAM modulated OFDM and STBC based OFDM over Frequency selective Rayleigh channel

V. CONCLUSION

In this paper, pilot aided channel estimation technique using comb type pilot arrangement with different interpolation method for STBC based OFDM system is investigated over multipath fading channel. The orthogonal properties of the pilot arrangement have been described in a great detail. Due to the orthogonal pilot arrangement between the two transmitting antennas, the channel estimation technique is simple and low computational cost as no matrix inversion is required. The simulation results shows that comb type pilot with spline and low-pass interpolation technique of STBC-OFDM system performs better than the conventional OFDM system. From the simulation result, it is clear that low-pass interpolation outperform than spline type interpolation method. We also see that SER decreases as number of receiving antenna increases. The developed channel estimation has a loss of 2dB to 2.5dB SNR as compared to the ideal case where it is assumed that the perfect channel knowledge is known at the receiver side. Hence from the simulation results and theory, it is proved that the developed channel estimation technique is best suitable for channel estimation purpose for multipath fading channel.

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