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Reduction of Co-Channel Interference and Estimation of Channel for Space-Time Based OFDM system over Doubly Selective Channel

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ABSTRACT

The performance analysis of Alamouti Space Time Block Code (STBC) based Orthogonal Frequency Division Multiplexing (OFDM) is often analyzed by assuming that the channel is constant over Alamouti code period (two consecutive OFDM symbol block). However, in fast fading channel, this assumption does not hold good and causes Co-channel Interference (CCI). Hence, the simple Alamouti detection method is not sufficient to recover the original transmitted signal from the mixed transmitted signals at the receiver side. To cancel the effects of CCI, several detection techniques are addressed namely SIC, DMLD, DZFD, DF and ML. The ML method has the optimum performance but the computational complexity is very high. Therefore, recently we have proposed a suboptimal MDF detection which provides comparable performance to that of ML with very less computational complexity. However, in such systems, the channel state information (CSI) is required to know at the receiver side in order to implement these detection schemes. Hence, we have proposed two channel estimation techniques which estimate the channel and thereby cancel the CCI effects coherently. The theory and simulation results validate the proposed scheme for STBC-OFDM system in high mobility multipath environment.

Keywords: STBC, OFDM ,CCI, Channel Estimation, Detection

1. INTRODUCTION

Adaptive filtering is one of the major subfield of digital 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]. 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. The frequency selective 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 [4]. However, in time varying fast fading channel the Alamouti STBC-OFDM system undergoes two types of interferences namely Inter-Carrier Interference (ICI) and Co-channel Interference (CCI) [5]. The ICI occurs due to the loss of orthogonality among the subcarrier within the OFDM symbol block. The CCI occurs due to the variation of channel frequency response (CFR) over Alamouti code period. Due to the CCI effect, the two consecutive transmitted OFDM symbol blocks are coupled with each other at the receiver side. Both the ICI and CCI cause significant performance degradation in time varying fast fading channel. However the power of CCI is proved to be 7-8 dB greater than the power of ICI regardless of the channel variation [5]. Hence, we only consider the CCI effect in Alamouti coded OFDM system. In literatures,

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various detection methods have been addressed for cancelling the effect of CCI [5]-[8]. In [6], a diagonalized maximum likelihood detector (DMLD) is proposed to remove the CCI. But the DMLD method has more computational complexity. Hence, a similar performance with low computational complexity zero forcing (DZFD) detector is proposed in [7]. A successive interference cancellation (SIC) method [5] is proposed, which has a low computational cost but its performance is not accurate enough due to the error propagation problem. The decision feedback (DF) method is proposed for STBC/SFBC OFDM system in [8]. The ML detection is studied in [7]-[8]. The ML method has the optimum performance but the computational complexity is very high.In this paper, we have analyzed the above detection methods and the proposed suboptimal modified DF (MDF) detection method to cancel the CCI effects.

In literatures, these detection techniques are applied by assuming that the complete channel state information (CSI) is known at the receiver side [5]-[8]. However, in practical scenario, 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 [10]. Such systems have 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. In literatures, many pilot aided techniques have been developed for channel estimation of OFDM system [11]-[13]. In [11], a comparison of channel estimation has been presented based on different modulation schemes and interpolation techniques. Linear, spline, second order, low pass interpolation (LPI) methods have been investigated in [12] and demonstrated that pilot aided channel estimation based on low pass interpolation LPI gives the best performance among all the interpolation technique. Pilot aided channel estimation has been proposed based on least square (LS) and minimum mean squared error (MMSE) algorithms for MIMO OFDM systems in [13]-[18] . One of the major problems in pilot symbol aided channel estimation for MIMO OFDM systems is the inter-transmitter-antennas-interference (ITAI). The ITAI arises when two transmitted signal are mixed at the receiver side and hence it is difficult to separate these transmitted signals. In [13] two pilot aided channel estimation approaches has been proposed to handle the ITAI problem namely zero-form and non-zero form pilot pattern [13]. Training based channel estimation with significant tap catching (STC) method is proposed to estimate the channel in [15] for STBC-OFDM for high mobility environment. EM based channel estimation for transmit diversity OFDM has been proposed in [16] to cancel the ITAI problem by decomposing the MIMO channel into several single input single output (SISO) channel. Instead of trainging based channel estimation comb-type pilot with STC has been applied to cancel the ITAI problem in OFDM system with transmit diversity [17]. However, most of the authors considered only the ITAI problem while estimating the channel and ignore the effective way of data detection by cancelling the CCI effects in STBC OFDM system. In [19], we have proposed a channel estimation technique which is based on least square (LS) algorithm with modified zero-form of comb type orthogonal pilot structure based on Alamouti principle at pilot subcarriers and LPI method is applied at data subcarriers. Although this method has the least computational complexity but it suffers from spectral efficiency due to the insertion of zeros at alternative pilot location.

Hence, in this paper, we have proposed a spectral efficient time domain channel estimation techniques jointly with various CCI cancellation methods in order to effectively recover the original transmitted data signal. The channel estimation method is based on LS algorithm to estimate the channel in time domain. As LS estimation involves matrix inversion, the computational complexity is intensive. Hence, the QR decompostion method is adopted to reduce the computational complexity by avoiding the matrix inversion.

The rest of the paper is organized as follows. In Section 2, the system model for the STBC OFDM system along with the channel model is discussed. Section 3 describes the conventional various detection

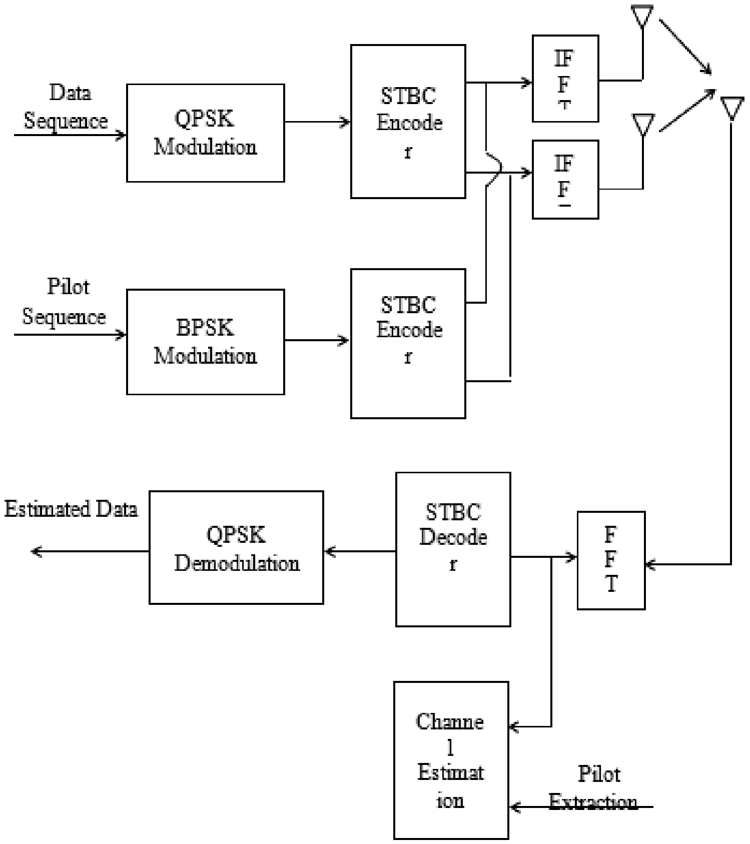

Figure 1: Baseband equivalent STBC OFDM system model

methods and a proposed MDF method to cancel the CCI effects. The proposed channel estimation technique is presented in Section 4. In Section 5, the performance of the developed channel estimation is analyzed. Finally, Section 6 concludes the paper.

2. SYSTEM MODEL

In this section, an STBC based OFDM system with two transmit antennas and one receive antennas is described along with the channel model.

2.1. STBC-OFDM System Model

The system model for STBC-OFDM with two transmit antenna and one receive antenna is shown in Fig. 1. At the transmitter side, a random data sequence is generated and modulated according to any specific modulation scheme such as BPSK, QPSK or 16QAM. Then the 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 Alamouti STBC scheme is described as follows. At the first time instant $X_1(k)$ and $X_2(k)$ are transmitted from the transmit antenna 1 and 2 respectively. In the second time instant $-X_2^*(k)$ and $X_1^*(k)$ are transmitted from antenna 1 and 2 respectively. Hence, the output of the STBC encoder can be written in matrix form as

$$X(k) = \begin{bmatrix} X_1(k) & X_2(k) \\ -X_2^*(k) & X_1^*(k) \end{bmatrix} \tag{1}$$

where $k = 0, 1, 2, ... N_s\text{-}1$

$X_i(k)$ is the k^{th} subcarrier for the i^{th} transmitting antenna before the IFFT operation and N_s is the total number of subcarrier in a single OFDM symbol block. Then, both the encoded output signal are passed through the serial to parallel converter (S/P) and OFDM modulated using Inverse Fast Fourier Transformation (IFFT) block. 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). At the receiver side, at first the CP is removed and then the received signal is processed by a Fast Fourier Transformation (FFT) operation. The FFT output of the received signal after the removal of CP can be written in the matrix form and is given below

$$Y(k) = \begin{bmatrix} Y_t(k) \\ Y^*_{t+T}(k) \end{bmatrix} = \underbrace{\begin{bmatrix} H_{1,t}(k) & H_{2,t}(k) \\ H^*_{2,t+T}(k) & -H^*_{1,t+T}(k) \end{bmatrix}}_{H} \underbrace{\begin{bmatrix} X_1(k) \\ X_2(k) \end{bmatrix}}_{X} + \underbrace{\begin{bmatrix} Z_t(k) \\ Z^*_{t+T}(k) \end{bmatrix}}_{Z} = HX + Z \tag{2}$$

where $H_{i,t}(k)$ denotes the CFR for i^{th} transmit antenna at the t^{th} time instant. $Z_t(k)$ is the circularly complex zero mean additive white Gaussian noise after the FFT operation. According to Alamouti scheme, the channel is considered to be static over two consecutive OFDM symbol block, i.e., $H_{1,t}(k) = H_{1,t+T}(k)$ and $H_{2,t}(k) = H_{2,t+T}(k)$. The STBC decoding operation is performed by multiplying H^H on both the side of (2). The original transmitted signal can be recovered after taking the hard decision of the decoded signal and can be written as

$$\hat{X}(k) = Q(\frac{\tilde{X}(k)}{\Phi(k)}) \tag{3}$$

where

$$\tilde{X}(k) = H^H(k)Y(k) \quad \text{and}$$
$$\Phi(k) = |H_{1,t}(k)|^2 +$$
$$|H_{2,t}(k)|^2 = |H_{1,t+T}(k)|^2 + |H_{2,t+T}(k)|^2$$

$\tilde{X}(k)$ is the decoded signal and Q denotes the hard decision function.Hence, the two estimated signals $\hat{X}(k)$ are decoupled from each other at the receiver side. However, in the fast fading channel,the channels are not same for two different time slots. Hence, $H^H H$ is no longer a orthogonal matrix and is given by

$$G = H^H H = \begin{bmatrix} \alpha_1(k) & \beta(k) \\ \beta^*(k) & \alpha_2(k) \end{bmatrix} \tag{4}$$

where

$$\alpha_1(k) = |H_{1,t}(k)|^2 + |H_{2,t+T}(k)|^2, \qquad \alpha_2(k)$$
$$= |H_{1,t+T}(k)|^2 + |H_{2,t}(k)|^2$$

and

$$\beta(k) = H^*_{1,t}(k)H_{2,t}(k) - H^*_{1,t+T}(k)H_{2,t+T}(k)$$

$a_1(k)$, $a_2(k)$ are the desired diversity gain terms and $\beta(k)$, $\beta*(k)$ are the CCI terms. By multiplying G with FFT output of the received signal Y, the detected output signal vector can be written as

$$\tilde{X}(k)=\begin{bmatrix}\tilde{X}_1(k)\\ \tilde{X}_2(k)\end{bmatrix}=\begin{bmatrix}\alpha_1(k)X_1(k)+\beta(k)X_2(k)+Z'_t(k)\\ \beta^*(k)X_1(k)+\alpha_2(k)X_2(k)+Z'_{t+T}(k)\end{bmatrix} \tag{5}$$

$\alpha_1(k)X_1(k)$ and $\alpha_2(k)X_2(k)$ are the desired signal. $\beta(k)X_2(k)$ and $\beta^*(k)X_1(k)$ are the CCI signal which are coupled with the desired signal at the receiver side. Hence, in order to accurately recover the original transmitted signal, these two CCI signals are to be cancelled.

2.2. Channel Model

The wireless channel model is assumed to be time selective as well as frequency selective fading channel (doubly selective). The frequency selective channel is employed as exponential decaying power delay profile (PDP) [20]. The channel is modeled as finite impulse response (FIR) with total $L+1$ non-zero path with zero mean and average power σ_l^2. The Rayleigh channel can be expressed as

$$h_l=N(0,\sigma_l^2/2)+jN(0,\sigma_l^2/2) \tag{6}$$

Where $N(0,\sigma_l^2/2)$ is the zero mean with variance σ_l^2. The power of multipath component decreases exponentially. The first path of the model can be written as

$$\sigma_0^2=\frac{1-\lambda}{1-\lambda^{L+1}} \qquad \lambda=e^{\frac{-T_S}{\tau_{rms}}} \tag{7}$$

where T_s and τ_{rms} are the sampling period and root mean squared (rms) delay of the channel. $T_s = 1/W$ and W is the channel (OFDM signal) bandwidth. The energy of the l^{th} path can be written as

$$\sigma_l^2=\sigma_0^2\lambda^l, \quad l=0,\ 1,\ 2,\ .....\ L \tag{8}$$

Furthermore, each multipath channel is modeled as uncorrelated Rayleigh fading channel with Jakes sum-of - sinusoidal (SOS) model [21]. The auto correlation of time varying frequency selective fading channel

$$E\left[h_l(n)\times h_l(m)^*\right]=\sigma_l^2\ J_0\left(2\pi(nn-m)F_dT_s\right) \tag{9}$$

where $h_l(n)$ is the l^{th} channel path with n^{th} time instant, $Jo()$ is the first kind Bessel function of zero order, F_d is the doppler frequency and F_dNT_s is the normalized Doppler spread.

3. DETECTION METHODS FOR CCI CANCELLATION

In this section, we describe different detection methods namely the SIC, DZFD, DF, ML and the proposed MDF methods in order to cancel the effects of CCI in the STBC based OFDM system over doubly selective channel.

3.1. SIC Detection Method

The successive interference cancellation method is proposed in [5]. Due to the time varying nature of channel, the two diversity gain terms are not same, but the gains of the two CCI terms are equal as given in the (5). Hence the SIC detection method is based on this gain difference property to recover the original transmitted signal and is illustrated below.

1. $\tilde{X}_1(k) = \alpha_1(k)X_1(k) + \beta(k)X_2(k) + Z'_t(k)$ (10)

2. $\tilde{X}_2(k) = \beta^*(k)X_1(k) + \alpha_2(k)X_2(k) + Z'_{t+T}(k)$ (11)

3. $if\ \alpha_1(k) > \alpha_2(k)$

$$\hat{X}_1(k) = Q(\tilde{X}_1(k)/\alpha_1(k)) \tag{12}$$

$$\hat{X}_2(k) = Q((\tilde{X}_2 - \beta^*(k)\hat{X}_1(k))/\alpha_2(k)) \tag{13}$$

4. $else$

$$\hat{X}_2(k) = Q(\tilde{X}_2(k)/\alpha_2(k)) \tag{14}$$

$$\hat{X}_1(k) = Q((\tilde{X}_1 - \beta(k)\hat{X}_2(k))/\alpha_1(k)) \tag{15}$$

The SIC detection method gives better results than Alamouti method as it cancels the CCI effects successively. However it is not accurate enough to recover the original transmitted signal due to its error propagation problem.

3.2. DZFD Detection Method

In the time varying fast fading channel, multiplying H^H with H does not give a orthogonal matrix as explained in (4). In order to get an orthogonal matrix, a transform matrix is multiplied with the H matrix [11] and is given below

$$\Omega H = diag(\varphi_1, \varphi_2) \tag{16}$$

where φ_1 and φ_2 are the complex number.

After simplification of (13), the &™ can be written in the matrix form and is given below

$$\Omega = \begin{bmatrix} H^*_{1,t+T}(k) & H_{2,t}(k) \\ H^*_{2,t+T}(k) & -H_{1,t}(k) \end{bmatrix} \tag{17}$$

The φ_1 and φ_2 have the same value and is given by

$$\varphi = \varphi_1 = \varphi_2 = H^*_{1,t+T}(k)\, H_{1,t}(k) + H_{2,t}(k)\, H^*_{2,t+T}(k) \tag{18}$$

Substituting Ω in the place of H^H, the decoded signal $\tilde{X}$ can be written as

$$\tilde{X} = \Omega Y = diag(\varphi, \varphi)X + \Omega Z \tag{19}$$

The estimated original transmitted signal can be obtained by dividing the value of φ on both side of (19) and then taking the hard decision

$$\hat{X}_1(k) = Q(\frac{\tilde{X}_1(k)}{\varphi(k)}) = X_1 + Z \tag{20}$$

$$\hat{X}_2(k) = Q(\frac{\tilde{X}_2(k)}{\varphi(k)}) = X_2 + Z \tag{21}$$

The DZFD detection method is simple as it simply forces the two CCI terms to zero but suffers from noise enhancement problem.

3.3. DF Detection Method

The DF detector was proposed for STBC-OFDM system in [8]. The working principle of DF detection method is described as follows. The DF first estimated a signal and then uses this estimated signal to help make decision about the other estimated signal by assuming that the first estimated signal is correct. The algorithm of DF detection method is given below.

1. Estimate the first signal $\hat{\mathrm{X}}_1$ using the DZFD detection method as given in (20).
2. Cancel the contribution of $\hat{\mathrm{X}}_1$ by subtracting it from the mixed detected output signal in (11). Then take the hard decision to obtain the estimated signal. The estimated signal $\hat{\mathrm{X}}_2$ can be written as

$$\hat{X}_2(k) = Q((\tilde{X}_2 - \beta^*(k)\hat{X}_1(k))/\alpha_2(k)) \tag{22}$$

The DF suppresses the noise enhancement problem and hence gives better result than DZFD.

3.4. ML Detection Method

The ML detection estimates all possible combination of transmitted signal and chose the most probable one. The ML detection can be written mathematical as

$$\hat{X}(k) = \underset{X_1, X_1 \in C_M}{\arg\min} \left\| Y(k) - H(k) \begin{bmatrix} X_1 \\ X_2 \end{bmatrix} \right\|^2 \tag{23}$$

where C_M denotes the constellation points.

ML detection requires $|C_M|^2$ times matrices calculation to solve (24) in order to estimate the original transmitted signal in the receiver side and hence is not preferable from the hardware implementation perspective.

3.5. Modified DF (MDF) Detection Method

The MDF method is the combination of modified SIC and DZFD method. The MDF method chooses the estimated signal coming from DZFD method and then cancels their contributions based on gain diversity property as given in SIC method with some modification. The algorithm for MDF detection method is given below

1.

$$if\ \alpha_1(k) > \alpha_2(k)$$

$$\bar{X}_1(k) = Q((\tilde{X}_1(k)/\varphi) \tag{24}$$

$$\breve{X}_2(k) = Q((\tilde{X}_2 - \beta^*(k)\bar{X}_1(k))/\alpha_2(k)) \tag{25}$$

$$\hat{X}_1(k) = Q((\tilde{X}_1 - \beta(k)\breve{X}_2(k))/\alpha_1(k)) \tag{26}$$

2. *else*

$$\bar{X}_2(k) = Q((\tilde{X}_2(k)/\varphi) \tag{27}$$

$$\breve{X}_1(k) = Q((\tilde{X}_1 - \beta(k)\bar{X}_2(k))/\alpha_1(k)) \tag{28}$$

$$\hat{X}_2(k) = Q((\tilde{X}_2 - \beta^*(k)\breve{X}_1(k))/\alpha_2(k)) \tag{29}$$

The proposed MDF method outperforms all the above detection methods except the ML method as it takes the advantages of both DZFD and modified SIC methods.

4. CHANNEL ESTIMATION

The channel estimation for STBC OFDM is generally performed by assuming that the channel is constant over two consecutive OFDM symbol blocks. But in fast fading channel, the CFR are not identical for two different time slots i.e. $H_{1,t}(k) \neq H_{1,t+T}(k)$ and $H_{2,t}(k) \neq H_{2,t+T}(k)$. Hence, in order to perform perfect data detection, all the entire four channels ($H_{1,t}(k)$, $H_{1,t+T}(k)$, $H_{2,t}(k)$ and $H_{2,t+T}(k)$) have to be estimated. To estimate the above mentioned four channels, we use comb type pilot aided channel estimation technique. The first estimation method is in frequency domain where as other in time domain.

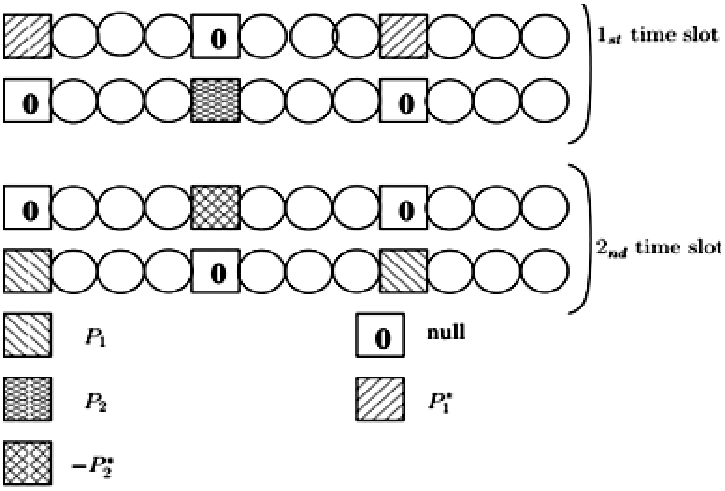

Figure 2: Proposed 1 pilot arrangement pattern

4.1. Frequency Domain Channel Estimation

In this sub section, at first we have presented our previously proposed estimation technique [19]. The pilot scheme is shown in the Fig. 2. The pilot subcarriers are designed in such a way that when one transmitting antenna transmits the pilot the other antenna is assumed to be silent and vice-versa. This assumption prejudicially avoids the ITAI effect. In this method, the four channels are estimated independently thus cancelling the effect of CCI. The channel estimation is carried out by LS algorithm. After estimating the channel at pilot subcarriers LPI has been applied to estimate the channel at data subcarriers. LPI method is chosen for its better performance in fast fading scenario. The position of the pilot subcarriers during first time slot at antenna 1 is P_1 and at antenna 2 is P_2. Arrangement of P_1 and P_2 can be given as (24) and (25) respectively

$$P_1 = \left[p_1, 0, p_3, 0, p_5, ...2N_p - 1 \right] \tag{30}$$

$$P_2 = \left[0, p_2, 0, p_4, 0, p_6 ....2N_p \right] \tag{31}$$

where, N_p stands for the total number of pilot subcarriers in a single OFDM symbol block.

During 2nd time slot, antenna 1 transmits $-P_2^*$ and antenna 2 transmits P_1^*. The received signal in the frequency domain at pilot sub-carriers for 1st time slot ($t = t$) and 2nd time slot ($t = t+T$) can be written in (26) and (27) respectively

$$Y_{t,p} = H^{p}_{1,t} P_1 + H^{p}_{2,t} P_2 + Z_t \tag{32}$$

$$Y_{t+T,p} = -H^{p}_{1,t+T} P_2^{*} + H^{p}_{2,t+T} P_1^{*} + Z_{t+T} \tag{33}$$

$P_{1,}$ P_2 are inserted uniformly (with zero padded at alternate locations) in each OFDM symbol block. The $H^{p}_{1,t}$, $H^{p}_{2,t}$, $H^{p}_{1,t+T}$ and $H^{p}_{2,t+T}$ are the four CFR at the pilot subcarrier of the four different channel paths. The four channels after LS algorithm are given by

$$H^{p}_{1,t} = Y_{t,p}(odd\ postions)\ /P_1(odd\ Positions) \tag{34}$$

$$H^{p}_{2,t} = Y_{t,p}(even\ postions)\ /P_2(even\ postions) \tag{35}$$

$$H^{p}_{1,t+T} = -Y_{t+T,p}(even\ postions)\ \ /P_2^{*}\ (even\ postions) \tag{36}$$

$$H^{p}_{2,t+T} = Y_{t+T,p}(odd\ postions)\ \ /P_1^{*}\ (odd\ postions) \tag{37}$$

In order to estimate the channel at data subcarrier by using channel information at pilot subcarrier, the interpolation technique is needed. The LPI technique is applied as it performs the best in time varying channel. 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 [11]. This estimation method has the lowest computational complexity due to element by element vector division operation only. But, the disadvantages of the developed channel estimation method is that it suffers from spectral efficiency due to the insertion of zeros at alternative pilot locations.

4.2. Time Domain Channel Estimation

At the transmitter side, pilot symbols are inserted uniformly into each OFDM symbol according to comb-type pilot arrangement. Let P_s and N_p denotes pilot subcarrier spacing and total number of pilot subcarriers in a single OFDM symbol block. The received pilot symbols for 1st time and 2nd time slot can be written as

$$\begin{aligned} Y_t^{p} &= diag(X_{1,t}^{p})F_{M\times L}h_{1,t} + diag(X_{1,t}^{p})F_L h_{2,t} + W_t^{p} \\ &= D_{1,t}^{P}F_{M\times L}h_{1,t} + D_{2,t}^{P}F_{M\times L}h_{2,t} + W_t^{p} \end{aligned} \tag{38}$$

$$\begin{aligned} Y_{t+T}^{p} &= -diag(X_{2,t}^{p^{*}})F_{M\times L}h_{1,t+T} + diag(X_{1,t}^{p^{*}})F_L h_{2,t+T} + W_{t+T}^{p} \\ &= -D_{2,t}^{P^{*}}F_{M\times L}h_{1,t+T} + D_{2,t}^{P^{*}}F_{M\times L}h_{2,t+T} + W_{t+T}^{p} \end{aligned} \tag{39}$$

$F_{N_p\times L}(n_p,l) = e^{-j2\pi\, n_p\, l/N}$ denotes the unitary DFT matrix, where $n_p = 0, P_{s,} 2P_{s,},..(N_p - 1)P_s$ are the corresponding rows and l denotes the first $L+1$ columns of the unitary matrix.

The equation (32) can be written in the matrix form as

$$Y_t^{p} = \underbrace{\begin{bmatrix} D_{1,t}^{p}F_{M\times L} & D_{2,t}^{p}F_{M\times L} \end{bmatrix}}_{A} \underbrace{\begin{bmatrix} h_{1,t} \\ h_{2,t} \end{bmatrix}}_{h_t} + W_t^{p} \tag{40}$$

where, $D_{i,t}^{p} = \left[diag(X_{i,t}(0), X_{i,t}(P_S), \cdots, X_{i,t}(N_p - 1)P_S) \right]$, $h_t = [h_{1,t}{}^{T} h_{2,t}{}^{T}]^{T}$ denotes the time domain channel vector for t^{th} time slots and $h_{\beta,t} = [h_{\beta,t}(0), h_{\beta,t}(0), ...h_{\beta,t}(L-1)]$.

The LS estimate of $\hat{h}_t$ can be obtained as

$$\hat{h}_t = A^{+} Y_t^{p} = (A^{H} A)^{-1} A^{H} Y_t^{p} \tag{41}$$

A is an $N_p \times 2L$ matrix and (35) has a unique solution if number of pilots N_p should be greater than or equal to the number of transmit antenna times the number of channel tap $(L+1)$. The time domain estimated channel for $t+T^{\text{-}th}$ time slot $\hat{h}_{t+T}$ can be easily estimated similar to $\hat{h}_t$. $\hat{h}_{t+T} = [\hat{h}_{1,t+T}{}^{T} \hat{h}_{2,t+T}{}^{T}]^{T}$ denotes the estimated time domain channel vector for $t+T^{\text{-}th}$ time slot where $\hat{h}_{\beta,t+T} = [h_{\beta,t+T}(0), h_{\beta,t+T}(1), ...h_{\beta,t}(L)]$. After all the four time domain channel vector are estimated i.e. $\hat{h}_{\beta,t}$ and $\hat{h}_{\beta,t+T}$, the time domain signals are converted into frequency domain channel vectors. The CFR for β^{th} transmit antenna at the t^{th} time slotcan bewritten as $\hat{H}_{\beta,t} = F_{N\times L}\hat{h}_{\beta,t}$ where $F_{N\times L}$ is the unitary DFT matrix with the first L columns and $\hat{H}_{\beta,t} = \left[\hat{H}_{\beta}^{t}(0), \hat{H}_{\beta}^{t}(1), ...\hat{H}_{\beta}^{t}(N_p - 1) \right]$ are the CFR at data subcarriers for β^{th} transmit antenna at the t^{th} time slot. The LS estimation involves in $N_p \times 2L$ matrix inversions, which needs high computational complexity. Hence, in this paper we have adopted a low complexity QRD algorithm [20] to estimate the entire four channel as it avoids the matrix inversion problem.

4.3. QR Decomposition based Channel Estimation

The Algorithm for QR decomposition based channel estimation is given below

[Step 1] Decompose the matrix $A_{N_p \times 2L} = Q_{N_p \times N_p} \begin{bmatrix} R \\ 0 \end{bmatrix}_{N_p \times 2L}$ where Q is an orthonormal matrix and R is a $2L\times 2L$ upper triangular matrix, 0 is an $(N_p - 2L)\times 2L$ zero matrix.

[Step2] Multiply Q^{H} on both side (35) can be rewrite as

$$\begin{aligned} r_t\,(p) &= Q^{H} Y_t^{p} = Q^{H} Q R h_{\beta,t}^{p} + Q^{H} W_t^{p} \\ &= R h_{t,\beta}^{p} + n_t^{p} \end{aligned} \tag{42}$$

The Equation (36) can be written in matrix form as

$$\begin{bmatrix} r_t\,(0) \\ r_t\,(1) \\ \vdots \\ r_t\,(2L-1) \\ \vdots \\ r_t\,(N_p - 1) \end{bmatrix} = \begin{bmatrix} R_{1,1} & R_{1,2} & \cdots & \cdots & R_{1,2L} \\ 0 & R_{2,2} & R_{2,3} & \cdots & R_{2,2L} \\ 0 & 0 & R_{3,3} & \cdots & R_{3,2L} \\ \vdots & \vdots & \vdots & \ddots & R_{2L,2L} \\ 0 & 0 & 0 & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \cdots & 0 \end{bmatrix} \begin{bmatrix} h_t(0) \\ h_t(1) \\ \vdots \\ \vdots \\ h_t(2L-2) \\ h_t(2L-1) \end{bmatrix} + \begin{bmatrix} n_t\,(0) \\ n_t\,(1) \\ \vdots \\ n_t\,(2L-1) \\ \vdots \\ n_t\,(N_p - 1) \end{bmatrix} \tag{43}$$

[Step 3] Estimate the channel h_t using the back substitution algorithm

At first, $r_t\ (2L-1)$ can be obtained from the matrix equation () and then $\hat{h}_t(2L-1)$ is estimated and can be written as

$$r_t^p(2L-1) = R_{2L,2L}h_t(2L-1) + n_t^p(2L-1) \tag{44}$$

$$\hat{h}_t(2L-1) = r_t^p(2L-1) / R_{2L,2L} \tag{45}$$

By using the estimated value $\hat{h}_t(2L-1)$ given in (39), the rest of the channel tap of $\hat{h}_t$ are estimated using recursive algorithm and are given by

$$\hat{h}_t(i) = (r_t^p(i) - \sum_{j=i+1}^{2L-1} \hat{h}_t(i)) / R_{i,i} \qquad i = 2L-2, ..., 1, 0 \tag{46}$$

The estimated CIR for $\hat{h}_{t+T}$ can be obtained similar to $\hat{h}_t$ using QR decomposition algorithm. Then, the time domain channel is converted into frequency domain channel at data subcarrier by multiplying the time domain channel with unitary DFT matrix. We call the proposed estimation method based on based on modified zero form comb-type pilot arrangement and LS-QRD methods as proposed 1 and proposed 2 estimation method respectively for the comparison of two methods. After getting the four CFR at data subcarriers, different CCI cancellation techniques have been applied to recover the original transmitted signal at the receiver side as given in the Section 3.

Table 1
Simulation Parameter

Parameter	*Value*
FFT Size	128
Number of Subcarrier	128
Number of CP	32
Data Modulation	QPSK
Pilot Modulation	BPSK
Pilot Arrangement	Comb-Type
Pilot Spacing	1:8
Carrier Frequency	5GHz
Channel BW	1MHz
Subcarrier Spacing	7.8125KHz
Channel Model	Exponential decaying PDP
Number of Multipath	4
RMS Delay spread	1us
Mobile speed	100/200 Km/h
Normalized Doppler frequency (F_dNTs)	0.06/0.12

5. SIMULATION RESULTS

The performance comparison of proposed and perfect channel estimation with different CCI cancellation methods including Alamouti, SIC, DZFD, DF, ML and MDF methods for STBC based OFDM system are carried out on the SER over various normalized Doppler spread. The simulation parameters used for simulation is listed on the Table1. Prefect time and frequency synchronization are assumed at the receiver side. Fig 2 shows, the performance comparison of conventional and proposed CCI cancellation decoders over mobile speed of 100Km/h under perfect channel estimation condition. The simulation results show that STBC OFDM with Alamouti method performs better than SISO OFDM but this method does not provide sufficient performance as it suffers severe performance degradation due to both CCI and ICI. The performance of SIC method is better than Alamouti detection method as it cancels the CCI effects successively but is not accurate enough due to error propagation problem. The DZFD detector simply forces the CCI signal to zero and gives better results than SIC method. But it suffers from noise enhancement problem. The DF gives better result than Alamouti, SIC and DZFD methods because it uses the first estimated signal correctly by using ZF detection method and then cancels its contribution from the mixed transmitted signal at the receiver side to estimate the other data signal. The MDF outperforms all the detection methods as it takes the advantages of both DZFD and SIC method but its performance is lesser than ML method. The computational complexity of various detection methods are given in Table 2.

From the table, it is seen that ML method has the highest whereas Alamouti method has the least computational complexity followed by DZFD, SIC, DF and MDF. We also see that MDF method achieves results comparable to the ML method with lesser computational complexity. The performance of various detection methods in the descending order are given as follows: ML, MDF, DF, DZFD, SIC and Alamouti.

Table 2
Computational Complexity

Methods	*Alamouti*	*SIC*	*DZFD*	*DF*	*MDF*	*ML*
Computational Complexity	8	12	10	21	24	$4(C_M)^2$
QPSK	8	12	10	21	24	64
16QAM	8	12	10	21	24	1024

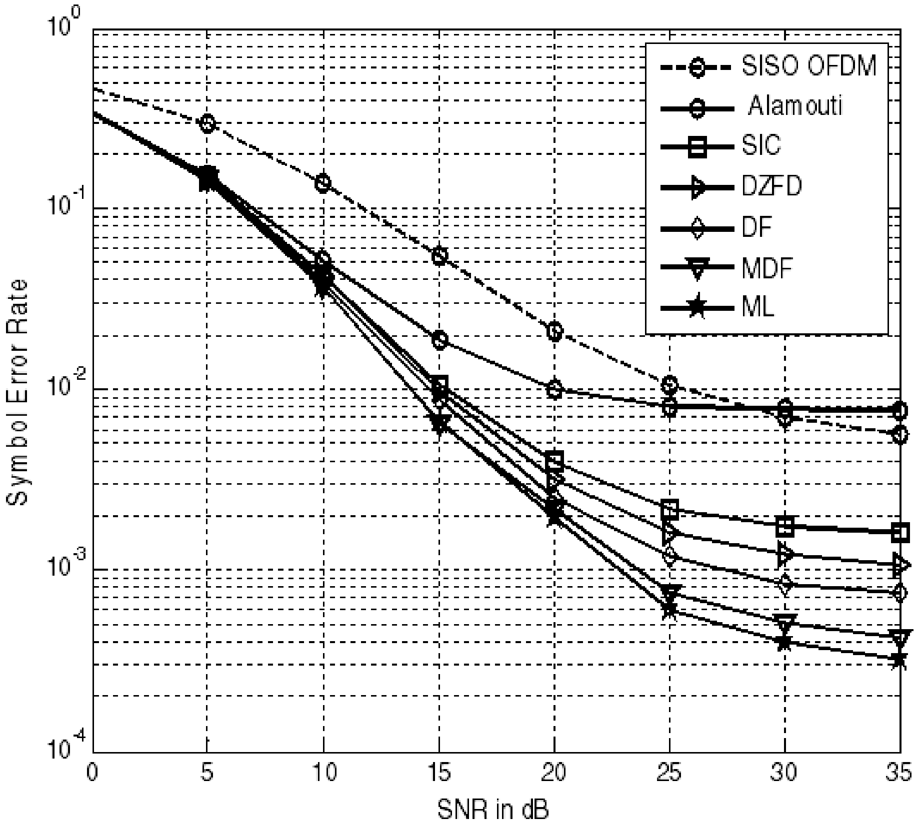

Figure 3: SER Performance comparision of different detection methods for normalized Doppler frequency of 0.06 under perfect channel estimation

The performance comparison of proposed and perfect channel estimations with various CCI cancellation methods are verified for normalized Doppler frequency of 0.06 and 0.12 are shown in the Fig 4 and Fig 5 respectively. From the simulation results, it is seen that, the method 1 channel estimated with different

CCI cancelation method outperforms the Alamouti perfect method at the high end of SNR. The simulation results show that the method 2 channel estimation has nearly the same performance with the perfect channel estimation and gives much better performance than method 1 channel estimation method. The performance of the method 1 decreases because interpolation is needed to estimate the CFR at the data subcarrier for which the noise is also interpolated in the entire data subcarriers. The proposed 1 estimation method involves only one tap division, hence its computational complexity is very lesser compared to proposed 2 channel estimation method. However, it suffers from spectral efficiency as twice the number of pilot symbols are used to estimate the channel. The SER performance with respect to normalized Doppler frequency is evaluated for various detection methods with perfect and proposed channel estimation at SNR = 25dB is shown in Fig 6. The simulation results show that, as the normalized Doppler spread (F_dNT_s) value increases, the performance of proposed and perfect estimation methods for various CCI cancellation methods decreases. The performance gap between the proposed and perfect channel estimation with various CCI cancellation decoders are increased as the F_dNT_s value increases. We also see that the proposed MDF method significantly outperforms the conventional methods as the mobile speed increases for both proposed and perfect channel estimation for STBC OFDM in doubly selective channel.

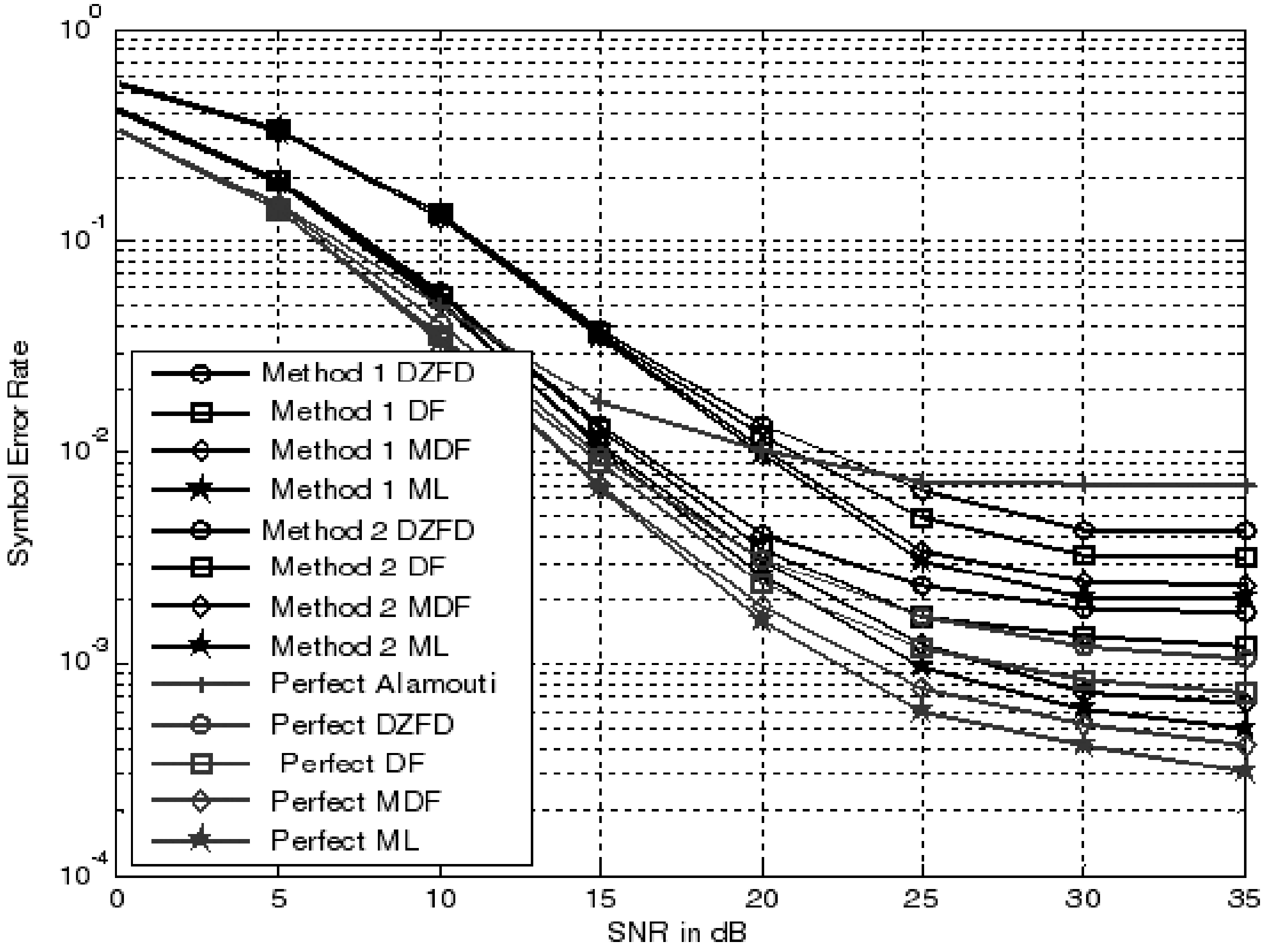

Figure 4: SER performance comparison of various detection methods with perfect and proposed channel estimation methods for normalized Doppler spread 0.06

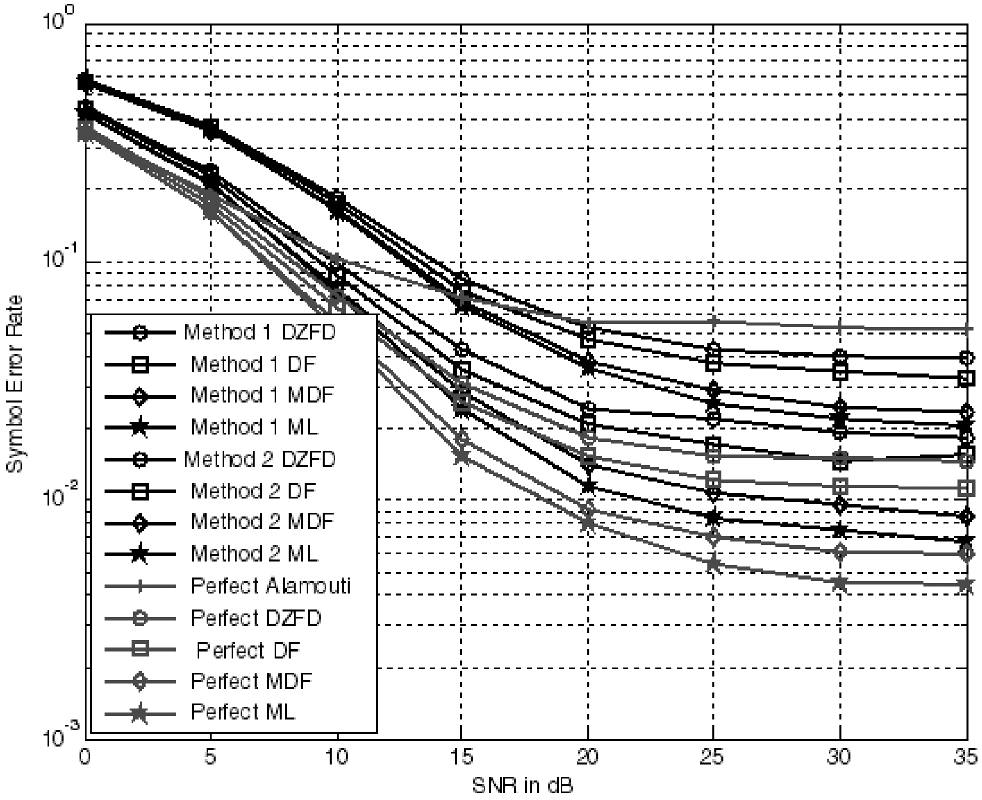

Figure 5: SER performance comparison of various detection methods with perfect and proposed channel estimation methods for normalized Doppler spread 0.12

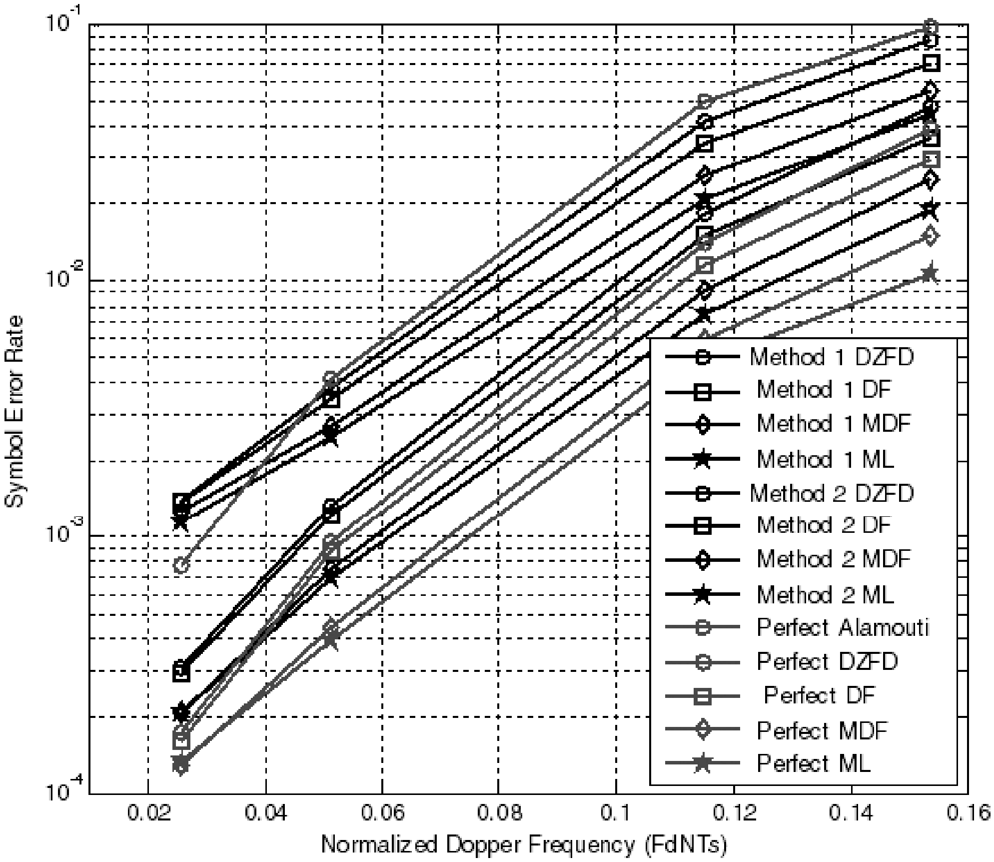

Figure 6: Performance comparison of various detection methods with perfect and proposed channel estimation methods with respct to $F_dNT_s$valueat SNR =25dB

6. CONCLUSIONS

In this paper, we have studied the combined effect of CCI cancellation and channel estimation for high mobility STBC-OFDM scheme. To cancel the CCI effect, various detection schemes including Alamouti, SIC, DZFD, DF, ML and MDF methods have been implemented. From the simulation results, it is seen that the MDF method achieves comparable performance to the ML method with a lesser computational complexity. However, the channel estimation is required at the receiver side in order to apply these detection schemes. We have presented two channel estimation techniques to estimate the channel and thereby cancelling the CCI effect. The first estimation method is based on LS algorithm with a modified zero form comb-type pilot arrangement. This estimation technique has the lowest computational complexity but suffers from low spectral efficiency. The second method is based on LS-QRD algorithm and has nearly performance to the perfect channel estimation where it is assumed that the complete channel knowledge is known at the receiver side. As compared to first method, second propose channel estimation method gives much better performance and spectral efficiency but the computational complexity is somewhat higher than that in first estimation method. These combined detection and channel estimation schemes can be further extended for more number of receive antennas to improve the system performances

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