Iterative Interference Cancellation for SFBC-OFDM System in Time Varying Multipath Fading Channel

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Abstract— **Alamouti coded Space Frequency Block Code (SFBC) based Orthogonal Frequency Division Multiplexing (OFDM) is very attractive due to its robustness against fast fading channel as the Channel Frequency Response (CFR) remain constant over Alamouti code period (two adjacent OFDM subcarrier). However, the channel is frequency selective as well as time selective. In frequency selective channel, the CFR are not constant for two adjacent OFDM subcarriers and hence leads to inter-symbol-interference (ISI) in SFBC-OFDM system. The inter-carrier-interference (ICI) also arises in OFDM system for time varying fast fading channel due to the loss of orthogonality among the subcarriers. Hence, both the ISI and ICI degrade the system performance for SFBC-OFDM system over time varying multipath fading channel. In this paper, we have proposed an iterative interference cancellation scheme which cancels the effect of ISI and ICI jointly. The proposed scheme cancels the interferences in two steps. In the first step, the Diagonalized Zero Forcing Detection (DZFD) method is used to suppress the effect of ISI. Then, in the second step, a simplified parallel interference cancellation (PIC) scheme coupled with decision statistics combining (DSC) is used to cancel the ICI effect and hence improves the system performance. The theory and simulation results verify that the proposed scheme achieves good performance in high time selective and high frequency selective channel environment for SFBC OFDM system.**

***Index Terms* — SFBC, OFDM, ISI, ICI, DZFD, PIC, DSC.**

1. Introduction

In recent years, link reliability and spectral efficiency are the most challenging requirements due to the application of audio, video and internet services in modern wireless communication systems [1]-[2]. The link reliability is solved by STBC which is proposed by Alamouti [3]. Originally, the STBC technique is applied to flat fading channel. But in practical scenario, the channel is frequency selective as well as time selective rather than flat fading. 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]. The use of OFDM also offers the other possibility of coding in the frequency dimension in a form of space frequency block code OFDM (SFBC-OFDM) [5]. The other important properties of OFDM are the spectral efficiency due to the orthogonality between the subcarriers and simplicity of implementation in the digital domain by the use of DFT [1]-[2]. The SFBC OFDM schemes are attractive in fast fading channel as the CFR are constant over Alamouti code period (two adjacent OFDM subcarriers). But when the channel is frequency selective, this assumption does not hold good and causes ISI [5]-[6]. Thus, due to the ISI effect, the received signal are not separated at the receiver side and the performances of the overall systems are degraded [6].The ICI also occurs in SFBC-OFDM system due to the loss of orthogonality among the subcarrier within the OFDM block in the time varying fast fading channel [6]-[7]. Hence, both the ISI and ICI effects cause significant performance degradation in time varying multipath fading channel.

In literature, various detection methods have been addressed for cancelling the effect of ISI and ICI for SFBC OFDM scheme in high mobility multipath fading channel. In [8], a Diagonalized Maximum Likelihood Detector (DMLD) is proposed to improve the system performance for SFBC OFDM and STBC-OFDM in both the multipath fading environments and the fast fading environments respectively. But the DMLD method is more computational complexity. Hence, a similar performance with low computational complexity DZFD is proposed in [9] for STBC OFDM in fast fading channel. This scheme can be easily extended to SFBC OFDM in frequency selective channel. Therefore, we use the DZFD scheme to improve the SFBC OFDM system performance by removing the ISI effect. The ICI cancellation techniques have been studied in various literature [6]-[7].The effect of ICI was first investigated in [10] and proposed a method to model the ICI effect as an additive Gaussian random process. Recently, the parallel interference cancellation scheme (PIC) along with DSC has been proposed to improve the MIMO OFDM system performance by removing the ICI effect [11]-[12].

Hence, in this paper, we have proposed a simplified low complexity two stages interference cancellation method to cancel both the ISI and ICI effect jointly for SFBC OFDM system in time varying multipath fading channel. In the first stage, we use the DZFD method to recover the original transmitted signal by removing the ISI effect.

In the latter stage, by using the DZFD data symbol, the ICI gain is estimated and is subtracted from the received signal by using a PIC module. In order to further improve the system performance, the output of the PIC module is passed through the DSC module, where the decision statistics signal is obtained by using the current and previous value iteratively [11]-[12].

The rest of the paper is organized as follows. In Section 2, the system model for the mobile OFDM, SFBC based OFDM system along with the channel model are discussed. The conventional DZFD detection method and the proposed interference cancellation scheme are presented in Section 3. In Section 4, the performance of these detection methods are compared on the basis of SER. Finally, Section 5 concludes the paper.

2. SYSTEM MODEL

In this section, at first the OFDM system model for high mobility environment is described and analyzed and then it is extend to SFBC OFDM case. After that, the channel model is described which is based on exponential decaying power delay profile with jakes sum of sinusoidal (SOS) channel model as time varying multipath Rayleigh fading channel.

A. OFDM System

Consider an OFDM system model with N subcarriers. X_k denotes the frequency domain data symbol for the k-th subcarrier. Then, the frequency domain data symbols are passed through the Inverse Fast Fourier Transformation (IFFT) block to convert into time domain sample and can be expressed as

$$x(n) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X(k) e^{\frac{j2\pi kn}{N}} + w(n) \tag{1}$$

where $n, k = 0, 1, 2, \ldots\ldots. N-1$

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, the time domain signal after removal of CP is expressed as

$$y(n) = \sum_{l=0}^{L-1} h(n,l) x(n-l) + w(n) \tag{2}$$

$h(n,l)$ is the channel impulse response of the n-th sample instant at the l-th channel tap in time domain. $x(n-l)$represents the $(n-l)$th sample instant and $w(n)$ is the Additive White Gaussian Noise (AWGN) at n-th sample instant. Equation (2) can be expressed as matrix form and is given below

$$y = hx + n \tag{3}$$

where $y = [y_0, y_1, \ldots\ldots\ldots, y_{N-1}]^T$, $x = [x_0, x_1, \ldots\ldots\ldots x_{N-1}]^T$ and $w = [w_0, w_1, \ldots\ldots\ldots w_{N-1}]^T$

h is an N x N time domain channel matrix with element given by $h(n, l) = h(n,(n-l)_N)$ where $h(n, l)$ is the channel impulse response at lag l for $0 < l < L-1$ and time instant n for $0 < n < N-1$.

After FFT operation, the received frequency domain signal at the k-th subcarrier is given as

$$Y(k) = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} y(n) e^{\frac{-j2\pi nk}{N}} + W_k \tag{4}$$

Substitute Equation (2) into Equation (4), the result can be expressed as

$$Y(k) = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} \sum_{l=0}^{L-1} h(n,l) x(n-l) e^{\frac{-j2\pi nk}{N}} + W_k \tag{5}$$

Applying Equation (1) into Equation (5), the received signal can be expressed as

$$Y(k) = \frac{1}{N} \sum_{m=0}^{N-1} \sum_{n=0}^{N-1} \sum_{l=0}^{L-1} h(n,l) e^{\frac{-j2\pi n(k-m)}{N}} e^{\frac{-j2\pi ml}{N}} X(m) + W(k)$$

$$= H(k,k) X(k) + \sum_{\substack{m=0 \\ m \neq k}}^{N-1} H(k,m) X(m) + W(k) \tag{6}$$

where

$$H(k,k) = \frac{1}{N} \sum_{l=0}^{L-1} h_{ave}(l) e^{\frac{-j2\pi kl}{N}}$$

$$h_{ave} = \frac{1}{N} \sum_{n=0}^{N-1} h(n,l)$$

$$H(k,m) = \frac{1}{N} \sum_{m=0}^{N-1} \sum_{l=0}^{L-1} h(n,l) e^{\frac{-j2\pi n(k-m)}{N}} e^{\frac{-j2\pi ml}{N}}$$

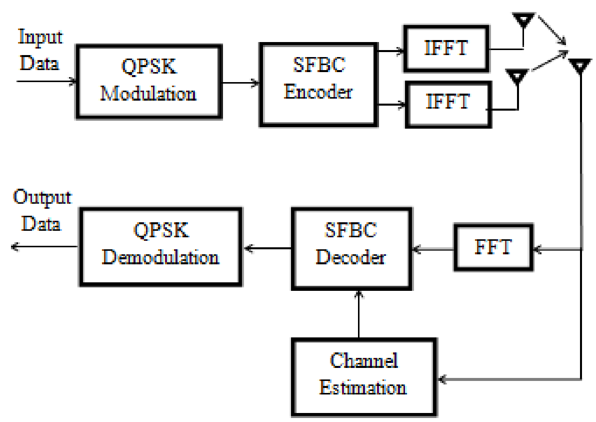

Fig.1 Block diagram of an SFBC-OFDM system model

B. SFBC-OFDM System Model

The SFBC OFDM is formed over space and frequency domain. The schematic diagram of SFBC-OFDM for two transmit antenna and one receive antenna is shown in the Fig 1. The data sequence is generated, modulated and passed into the SFBC encoder.

The SFBC encoder converts the modulated output data sequence $X(k)$ into two data vector $X_1(k)$ and $X_2(k)$ and are given by

$$X(k) = \left[s_0, s_1, s_2, s_3, \ldots\ldots\ldots\ \ldots\ldots s_{N-2}, s_{N-1}\right]$$
$$X_1(k) = \left[s_0, -s_1^*, s_2, -s_3^*, \ldots\ldots\ldots\ \ldots\ldots s_{N-2}, -s_{N-1}^*\right] \quad (7)$$
$$X_2(k) = \left[s_1, s_0^*, s_3, s_2^*, \ldots\ldots\ldots\ \ldots\ldots s_{N-1}, s_{N-2}^*\right]$$

For simplicity of operation, the SFBC-OFDM can be described in terms of even and odd components. Let $X_{1o}(k)$ $X_{1e}(k)$ $X_{2o}(k)$, $X_{2e}(k)$ be two length $N/2$ vectors denoting the odd and even component vectors $X_1(k)$ and $X_2(k)$

$$X_{1e} = X_e \qquad X_{1o} = -X_o^* \qquad (8)$$
$$X_{2e} = X_o \qquad X_{2o} = X_e^*$$

The FFT output of the received signal after the removal of CP can be written as

$$Y(k) = H(k,k)X(k) + \underbrace{\sum_{m=0, m\neq k}^{N/2-1} H(k,m)X(m)}_{I(k)} + W(k) \qquad (9)$$

The $Y(k), I(k)$ and $W(k)$ are the frequency domain received data symbol, ICI and AWGN channel respectively.
where

$$X(k) = [X_e(k)\ X_o(k)\ ]^T$$

$$H(k,m) = \begin{bmatrix} H_{1,e}(k,m) & H_{2,e}(k,m) \\ H_{2,o}^*(k,m) & -H_{1,o}^*(k,m) \end{bmatrix}$$

$$Y(k) = \begin{bmatrix} Y_e(k) & Y_o^*(k) \end{bmatrix}^T$$

$$W(k) = \begin{bmatrix} W_e(k) & W_o^*(k) \end{bmatrix}^T$$

$H_{1,e}(k,m)$ and $H_{2,e}(k,m)$ are the CFR for the first and second transmit antenna at the even time instant respectively. It is to be noted that $H_{1,e}(k,m)$ is an $N/2$ x $N/2$ channel matrix with subcarrier $k=m$ are the diagonal element and responsible for the frequency response of the time varying channel and the subcarrier $k \neq m$ are the non-diagonal elements and leads to ICI from the m-th subcarrier to the k-th.

At first, we ignore the effect of ICI and hence modelled the ICI signal as white Gaussian random process [10]. Thus, the Equation (9) can be reduced to

$$Y(k) = H(k,k)X(k) + J(k) \qquad (10)$$

where $J(k) = \underbrace{\sum_{m=0, m\neq k}^{N/2-1} H(k,m)X(m)}_{I(k)} + W(K)$

The STBC decoding operation is performed by multiplying $H^H(k,k)$ on both the side of the equation (10) and is written as

$$\tilde{X}(k) = H^H(k,k)Y(k) = G(k)X(k) + H^H(k,k)J(k) \qquad (11)$$

where

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

and $\alpha_1(k) = \left|H_{1,e}(k)\right|^2 + \left|H_{2,o}(k)\right|^2$

$$\alpha_2(k) = \left|H_{1,o}(k)\right|^2 + \left|H_{2,e}(k)\right|^2$$

$$\beta(k) = H_{1,e}^*(k)H_{2,e}(k) - H_{1,o}^*(k)H_{2,o}(k)$$

$\alpha_1(k)$, $\alpha_2(k)$ are the desired diversity gain terms and $\beta(k)$, $\beta^*(k)$ are the ISI terms. By multiplying $G(k)$, the detected output signal vector can be written as

$$\tilde{X} = \begin{bmatrix} \tilde{X}_e(k) \\ \tilde{X}_o(k) \end{bmatrix} = \begin{bmatrix} \alpha_1(k)X_e(k) + \beta(k)X_o(k) + Z'_e(k) \\ \beta^*(k)X_e(k) + \alpha_2(k)X_o(k) + Z'_o(k) \end{bmatrix} \qquad (12)$$

The original transmitted signal can be recovered after taking the hard decision of the decoded signal. $\alpha_1(k)X_e(k)$ and $\alpha_2(k)X_o(k)$ are the desired signal. $\beta(k)X_o(k)$ and $\beta^*(k)X_e(k)$ are the ISI signal which are coupled with the desired signal at the receiver side. Hence, in order to accurately recover the original transmitted signal, these two ISI signals are to be cancelled.

C. Channel Model

The wireless channel model is assumed to be time varying frequency selective fading channel. The frequency selective is employed as exponential power delay profile (PDP) [13]-[14]. 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

$$h_l = N(0, \sigma_l/2) + jN(0, \sigma_l/2) \qquad (13)$$

where $N(0,\sigma_l/2)$ 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

$$\sigma_0^2 = \frac{1 - e^{-\frac{1}{d}}}{1 - e^{-\frac{L+1}{d}}}, \quad d = \frac{\tau_{rms}}{T_s} \qquad (14)$$

d is the normalized delay spread τ_{rms} and is the root mean squared delay of the channel. $Ts = 1/W$, where W is the channel (OFDM signal) bandwidth.

The energy of the l-th path can be written as

$$\sigma_l^2 = \sigma_0^2 \lambda^l, \qquad l = 0,1,2,\ldots\ldots L\ . \qquad (15)$$

The total number of path is given by

$$L = \tau_{max}/Ts \quad, \tau_{max} = -\tau_{rms} \ln A \tag{16}$$

where τ_{rms} is the maximum excess delay and A is ratio of non-negligible path power to first path power. For high frequency selective channel, we have taken A = -20dB and d = 4 or 8. The total number of fading path for d = 4 and 8 is calculated to be 12 and 24 respectively.

Furthermore, each multipath is modeled as uncorrelated Rayleigh fading channel with Jakes sum-of-sinusoidal (SOS) model [15]. The auto correlation of time varying frequency selective fading channel can be written as

$$E\left[h_l(n) \times h_l(m)^*\right] = \sigma_l^2 J_0\left(2\pi\pi(-m)F_d T_s\right) \tag{17}$$

where $h_l(n)$ is the lth channel path with nth 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 of the channel.

3. PROPOSED INTERFERENCE SUPRESSION

Both the ISI and ICI degrade the SFBC OFDM system performance in time varying multipath fading channel. Hence, we have proposed an iterative interference cancellation scheme that cancels the ISI and ICI effect jointly. This method cancels the interference in two steps. In the first stage, we have adopted DZFD method to cancel the ISI effect before the ICI cancellation. In the second stage, the ICI cancellation has been performed iteratively by using PIC method couple with the DSC technique.

A. Conventional ZF Detection Method

We adopt the DZFD method to cancel the effect of ISI. In the frequency selective channel, multiplying H^H with H does not give an orthogonal matrix as explained in the Equation (11). In order to make the (11), an orthogonal matrix, a Ω matrix is multiplied with the H matrix [9] and is given below

$$\Omega H = diag(\varphi_1, \varphi_2) \tag{18}$$

where φ_1 and φ_2 are the complex number.

$$\Omega(k) = \begin{bmatrix} H^*_{1,o}(k) & H_{2,e}(k) \\ H^*_{2,o}(k) & -H_{1,e}(k) \end{bmatrix} \tag{19}$$

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

$$\begin{aligned} \varphi_1 &= \varphi_2 = \varphi \\ &= H^*_{1,o}(k) H_{1,e}(k) + H_{2,e}(k) H^*_{2,o}(k) \end{aligned} \tag{20}$$

Substituting Ω in the place of H^H, the equation (11) becomes

$$\widetilde{X}(k) = \Omega(k)Y(k) = diag(\varphi, \varphi)X(k) + \Omega(k)J(k) \tag{21}$$

The estimated original transmitted signal can be obtained by dividing the value of φ on both the side and then taking the hard decision and is given by the Equation (22)

$$\hat{X}(k) = Q\left(\frac{\widetilde{X}(k)}{\varphi(k)}\right) \tag{22}$$

where Q is the hard decision function. The DZFD method cancels the ISI effect and hence gives better result than Alamouti detection method. The DZFD is not accurate enough as ICI effect is still present in the system. Hence, both the ISI and ICI cancellation should be performed jointly.

B. Proposed Interference Cancellation Method

The proposed cancellation scheme cancels both the ISI and ICI interferences jointly. The interference cancellation has been performed in two stages. In the first stage, we cancel the ISI effect by using DZFD method and then take the hard decision to get the decoded signal which is free from CCI effect. In the second stage, we cancel the ICI effect in the iterative process. In order to cancel the ICI effect, the ICI gain term has to be estimated and subtracted it from the received signal. The output of the received signal in the *I-th* iteration at the *k-th* subcarrier is given by

$$Y^I_{off\ ICI}(k) = Y(k) - \sum_{m=0, m\neq k}^{N-1} H(k,m)\hat{X}^{I-1}(m) \tag{23}$$

where

$$Y^I_{off\ ICI}(k) = \begin{bmatrix} Y^I_{e\ off\ ICI}(k) & Y^I_{o\ off\ ICI}(k) \end{bmatrix}^T$$

$$\hat{X}^{I-1}(m) = \begin{bmatrix} \hat{X}_e^{I-1}(m) & \hat{X}_o^{I-1}(m) \end{bmatrix}^T$$

$\hat{X}_e^{I-1}(m)$ denotes the even estimated information symbol from the output of DZFD for the *m-th* subcarrier in the *I-th* iteration after taking the hard decision function.

The decision statics received signal can be obtained by applying one-tap ZF equalization technique to the modified ICI free received signal given in the Equation (23) and is written as

$$R^I(k) = \left(H(k,k)\right)^{-1} * \left(Y^I_{off\ ICI}(k)\right) \tag{24}$$

In high interference scenario, the detector output in the second iteration biased towards the decision boundary. Thus, a combing method called DSC is proposed in [11]-[12] to improve the SNR. The decision statistics is generated by the DSC module as a weighted sum of current PIC output $R^I(k)$ and the decision statics of the previous iteration $R^{I-1}_{DSC}(k)$ and is given by

$$R^I_{DSC} = \frac{(\sigma^{I-1}_{DSC})^2}{z} R^I + \frac{(\sigma^I)^2}{z} R^{I-1}_{DSC} \tag{25}$$

where $z = (\sigma^{I-1}_{DSC})^2 + (\sigma^I)^2$

$(\sigma^{I-1}_{DSC})^2$ and $(\sigma^I)^2$ are the variance of the DSC estimate output (R^{I-1}_{DSC}) and the PIC output (R^I)respectively. The decision statistics of each iterative stage is updated by the hard decision output generated from the demodulator.

The output of the decision statistics received signal is then passed through the hard decision function to get the decoded received signal and is given by

$$\hat{X}^{I}(k) = Q(R^{I}(k)) \tag{26}$$

In order to reduce the complexity of the system, we consider only the ICI gain term from $2q$ neighboring subcarrier and ignore rest of the subcarriers that is

$$H(k,m) = 0 \qquad |k-m| > q \quad \text{and} \quad q << N \tag{27}$$

Substituting the assumption given in the Equation (27), the Equation (23) can be greatly simplified to

$$Y^{I}_{off\ ICI}(k) = Y(k) - \sum_{m=k-q, m\neq k}^{m=k+q} H(k,m)\hat{X}^{I-1}(m) \tag{28}$$

where $2q$ is the number of term contributing the ICI effect.

The most of the computational of the proposed algorithm is coming from the equation (23). Since the interference coming from all of the subcarrier, the computational complexity is $O(N^2)$. As we restrict our ICI term gain term only for $2q$ neighboring subcarrier, the computational complexity is greatly reduced to $O((2q+1)N))$

Table1 Simulation Parameter

Parameter	Value
FFT Size	128
Number of Subcarrier	128
Number of CP	32
Data Modulation	16QAM
Carrier Frequency	5 GHz
Channel BW	1 MHz
Channel Model	Exponential decaying PDP
Number of Multipath	12/24
Normalized RMS delay spread (d)	4 / 8
Mobile speed	200 Km/h
Normalized Doppler spread (F_dNTs)	0.12

4. SIMULATION RESULTS AND DISCUSSION

In this section, the performance comparison of conventional detection methods including Alamouti, DZFD and the proposed methods are carried out on the basis of SER for SFBC based OFDM system in highly frequency selective time varying fading channel. The total simulation parameter used for the simulation process is given in the Table 1. Prefect synchronization and prefect channel knowledge is assumed at the receiver side. The SER performance for Alamouti, conventional DZFD and the proposed detection methods for normalized RMS delay spread of d=4 and d=8 and mobile speed of 200Km/h (normalized Doppler frequency F_dNTs = 0.12) are shown in the Fig 2 and Fig 3 respectively. The simulation result shows that Alamouti method suffers severe performance degradation due to both ISI and ICI effects. The DZFD method simply cancel the ISI effect and hence gives better results than Alamouti detection method but is not accurate enough as ICI effect is still present in the system. The proposed interference cancellation scheme outperforms the conventional above detection methods as it cancels both the ISI and ICI effect jointly. It cancels the interferences in two steps. In the first step, the ISI effect is cancelled by using DZFD method. In the second step it calculates the gain of ICI and cancels its effect iteratively by using PIC-DSC interference cancellation scheme, whereby at each iterative stage the reliability of data increases.

The simulations result shows that as the number of iteration stage increases, the SER decreases. In order to reduce the computational complexity, we consider only q=2 number of neighbouring subcarriers for the simulation process. The proposed scheme can also be extended to more number of receiving antennas to improve the system performance.

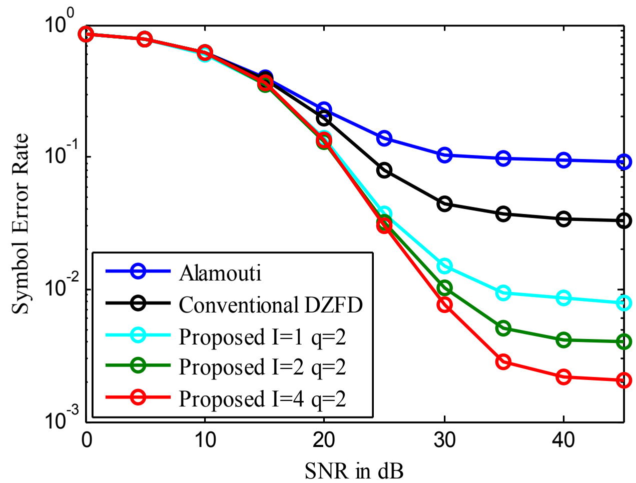

Fig.2 SER Vs SNR for different detection methods for normalized Doppler frequency of 0.12 and normalized delay spread d=4

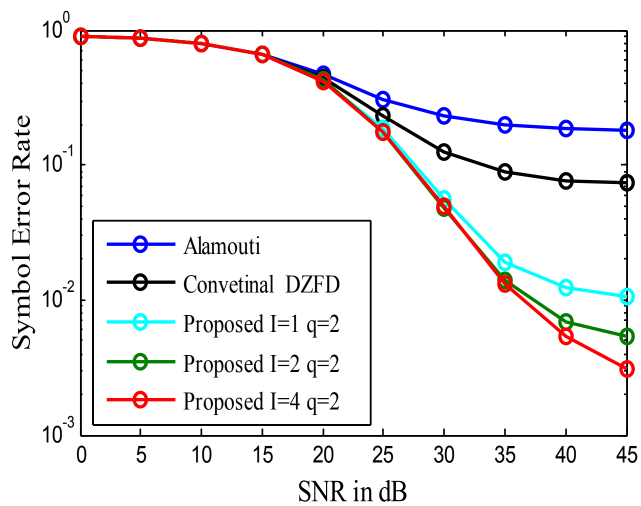

Fig.3 SER Vs SNR for different detection methods for normalized Doppler frequency of 0.12 and normalized delay spread d=8

5. CONLCUSION

The Alamouti coded SFBC OFDM system undergoes two types of interference namely ISI and ICI in time varying frequency selective fading channel. To mitigate the ISI effect, we have adopted the DZFD method and it performs better than Alamouti detection method but is not accurate enough as ICI effect is present in the system. Hence, we have purposed an iterative interference cancellation scheme which cancels the ISI and ICI effect jointly. The purposed method cancels the interference in two steps. In the first step, the CCI effect is cancelled by DZFD method. In the second step, the ICI gain is estimated by using DZFD information symbol and iteratively cancels its effect by using PIC coupled with DSC technique, whereby at each iterative stage the reliability of data increases. The complexity of the system is significantly reduced by using limited number of neighboring interference subcarriers. The theory and simulation results demonstrated that purposed scheme effectively improves the SFBC OFDM system performance in highly frequency selective mobile environment with less computational complexity.

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