Joint Iterative CCI and ICI Cancellation for STBC-OFDM System in Fast Fading 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 on the assumption that the channel is constant over Alamouti code period (two consecutive OFDM symbol block). But when the channel is fast fading, this assumption does not hold good and causes co-channel interference (CCI) and inter-carrier interference (ICI). In this paper, an iterative interference cancellation is proposed for STBC OFDM to suppress both the CCI and ICI effect jointly. The proposed scheme consists of two stage interference cancellation. In the first stage the CCI cancellation is performed based on Diagonalized Zero Forcing Detection (DZFD) method. In the latter stage a simplified parallel interference cancellation (PIC) scheme coupled with decision statistics combining (DSC) method is used to cancel the ICI effect and hence improves the system performance. The simulation results verify that the proposed scheme achieves good performance for STBC OFDM system in high mobility environment.**

Index Terms — STBC, OFDM, CCI, ICI, DZFD, PIC, DSC.

I. INTRODUCTION

Now a days, almost all wireless communication system are focusing on reliability and spectral efficiency [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]. However, in time varying fast fading channel the Alamouti STBC-OFDM system undergoes two types of interfering namely inter-carrier interference (ICI) and CCI [5]-[8]. The ICI is occurred due to the loss of orthogonality among the subcarrier within the OFDM block [9]-[10]. The CCI is occurred 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 [8].

In literature, various detection methods have been addressed for cancelling the effect of CCI and ICI for high mobility STBC OFDM scheme. In [5], a Diagonalized Maximum Likelihood Detector (DMLD) is proposed to remove the CCI. But the DMLD method is more computational complexity. Hence, a similar performance with low computational complexity Diagonalized Zero Forcing Detector (DZFD) is proposed in [6]. A successive interference cancellation (SIC) method is proposed in [8]. An iterative interference cancellation scheme based on List-SIC to cancel both CCI and ICI effect jointly for time varying STBC OFDM is proposed in [7], where the performance is improved but the computational complexity increases due to List-SIC method.

Hence, in this paper, we have proposed a simplified low complexity two stage interference cancellation method to suppress both the CCI and ICI effect jointly for high mobility STBC OFDM scheme. In the first stage, the CCI cancellation method is applied by using the DZFD method to recover the data symbol. 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 parallel interference cancellation (PIC) [11]-[12] 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.

The rest of the paper is organized as follows. In Section II, the system model for mobile OFDM and STBC-OFDM system are discussed. The conventional DZFD detection method and the proposed interference cancellation scheme are presented in Section III. In Section IV, the performance of these detection methods are compared on the basis of SER. Finally, Section V concludes the paper.

II. 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 STBC OFDM case. After that, the channel model is described which is based on exponential 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 $n, k = 0, 1, 2, ...N-1$

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

$$y = h\,x + n \tag{3}$$

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

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 (CIR) 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

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

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

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

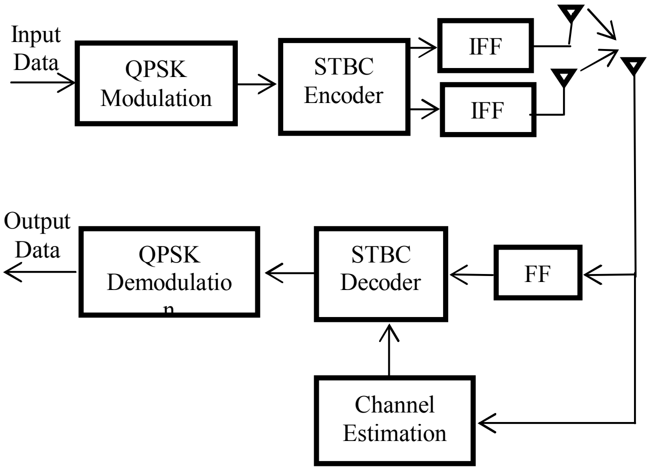

Fig.1 Block diagram of an STBC-OFDM system model

B. STBC-OFDM System Model

The system model for STBC-OFDM with two transmit antenna and one receive antenna is shown in the Fig1. For two transmit antennas two OFDM data symbol are grouped into one data symbol vector and can be written as

$$X(k) = [X_1(k) \quad X_2(k)]^T \tag{7}$$

$X_1(k)$ is the *k-th* subcarrier for the transmitting antenna 1 before the IFFT operation and N is the number of subcarrier in a single OFDM symbol block.

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.

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

$$Y(k) = H(k,k)X(k) + \underbrace{\sum_{m=0, m\neq k}^{N-1} H(k,m)X(m)}_{I(k)} + W(k) \tag{8}$$

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

where

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

$$Y(k)=\begin{bmatrix} Y_{1,t}(k) & Y_{1,t+T}{}^*(k) \end{bmatrix}^T$$

$$W(k)=\begin{bmatrix} W_{1,t}(k) & W_{1,t+T}{}^*(k) \end{bmatrix}^T$$

where $H_{1,t}(k,m)$ and $H_{2,t}(k,m)$ are the CFR for the first and second transmit antenna at the first time instant respectively.

It is to be noted that $H_{1,t}(k,m)$ is an N x N 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* subcarrier between the first transmit antenna to the received antenna at the *t-th* time slot.

At first, we ignore the effect of ICI and hence the ICI signal can be modelled as white Gaussian process [9]. Thus, the Equation (8) can be reduced to

$$Y\,(k) = H(k,k)X(k) + J(k) \tag{9}$$

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

The STBC decoding operation is performed by multiplying $H^H(k,k)$ on both the side of the equation (9) and can be written as

$$Z(k) = H^H(k,k)Y(k) = G(k)X(k) + H^H(k,k)J(k) \tag{10}$$

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

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

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

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

$$\tilde{X} = \begin{bmatrix} \tilde{X}_1(k) \\ \tilde{X}_2(k) \end{bmatrix} = \begin{bmatrix} \alpha_1(k)X_1(k) + \beta(k)X_2(k) + Z'_t(k) \\ \beta^*(k)X_1(k) + \alpha_2(k)X_2(k) + Z'_{t+T}(k) \end{bmatrix} \tag{11}$$

The original transmitted signal can be recovered after taking the hard decision of the decoded signal. $\alpha_1(k)X_1(k)$ 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.

C. *Channel Model*

In this paper, an exponential power delay profile (PDP) channel [13] is adopted for the STBC-OFDM system model. 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 channel can be expressed by

$$h_l = N(0,\frac{\sigma_l}{2}) + jN(0,\frac{\sigma_l}{2}) \tag{12}$$

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

$$\sigma_0^2 = \frac{1-\lambda}{1-\lambda^{L+1}} \tag{13}$$

where $\lambda = e^{-\frac{T_S}{\tau_{rms}}}$

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

$$\sigma_l^2 = \sigma_0^2\lambda^l\,. \tag{14}$$

Furthermore, each multipath is modeled as uncorrelated Rayleigh fading channel with Jakes sum-of-sinusoidal (SOS) model [14].The auto correlation of time varying frequency selective fading channel can be written as

$$E\left[h_l(n) \times h_l(m)^*\right] = \sigma_l^2 J_0\left(2\pi\pi(-m)F_dT_s\right) \tag{15}$$

where $h_l(n)$ is the *l-th* 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.

III. PROPOSED INTERFERENCE SUPRESSION

Both the CCI and ICI degrade the STBC OFDM system performance in time varying channel. Hence, the proposed method is to cancel both the CCI and ICI effect jointly. This method consists of two steps interference cancellation. It can be seen that the power of CCI is greater than the power of ICI regardless of the channel variation [8]. Hence, in the earlier stage, the CCI cancellation has to be performed before the ICI cancellation. The CCI cancellation has been done by using DZFD method proposed in [6]. In the latter 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 CCI.In the time varying fast fading channel, multiplying H^H with H does not give an orthogonal matrix as explained in the equation (10). In order to make the equation (10), an orthogonal matrix, a Ω matrix is multiplied with the *H* matrix [5] and is given below

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

where φ_1 and φ_2 are the complex number.

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

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

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

Substituting Ω in the place of H^H, the equation (2) becomes

$$\widetilde{X}(k) = \Omega(k) Y(k) = diag(\varphi, \varphi) X(k) + \Omega(k) J(k) \tag{19}$$

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

$$\hat{X}(k) = Q\left(\frac{\widetilde{X}(k)}{\varphi(k)}\right) \tag{20}$$

where Q is the hard decision function. The DZFD method cancels the CCI effect but is not accurate enough as ICI effect is still present in the system. Hence, both the CCI and ICI cancellation should be cancelled jointly.

B. Proposed Interference Cancellation Method

The proposed cancellation scheme cancels both the CCI and ICI interferences jointly. The interference cancellation has been performed in two stages. In the first stage, we cancel the CCI 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

$$Y^I{}_{off\ ICI}(k) = Y(k) - \sum_{m=0, m\neq k}^{N-1} H(k,m) \hat{X}^{I-1}(m) \tag{21}$$

where $\hat{X}^{I-1}(m)$ denotes the information symbol detected from the DZFD and after the hard decision for the *m-th* subcarrier in the *I-th* iteration.

The decision statistics received signal can be obtained by applying one-tap ZF equalization method to the modified ICI free received signal and given in the equation (22)

$$R^I(k) = H(k,k)^{-1} * Y^I{}_{off\ ICI}(k) \tag{22}$$

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

$$\hat{X}^I(k) = Q(R^I(k)) \tag{23}$$

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

$$R^I_{DSC} = \frac{(\sigma^{I-1}_{DSC})^2}{z} R^I + \frac{(\sigma^I)^2}{z} R^{I-1}_{DSC} \tag{24}$$

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 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.

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

$$H(k,m) = 0 \qquad |k - m| > q \quad \text{and} \quad q << N \tag{25}$$

Substituting the assumption given in the Equation (25), the equation (21) can be greatly simplified to

$$Y^I{}_{off\ ICI}(k) = Y(k) - \sum_{m=k-q, m\neq k}^{m=k+q} H(k,m) \hat{X}^{I-1}(m) \tag{26}$$

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 (21). 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	16
Data Modulation	QPSK
Carrier Frequency	5 GHz
Channel BW	1 MHz
Subcarrier Spacing	7.8125 kHz
Channel Model	Exponential decaying PDP
Number of Multipath	3
Mobile speed	100/200 Km/h
Normalized Doppler frequency (f_dNTs)	0.06/0.12

IV. SIMULATION RESULTS AND DISCUSSIONS

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 STBC based OFDM system over various mobile speeds. 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, DZFD and proposed detection methods for mobile speed 100Km/h (normalized Doppler frequency $f_dNTs = 0.06$) and 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 CCI and ICI. The DZFD method simply forces the CCI signal to zero and gives better results than Alamouti detection method but is not accurate enough as ICI effect is still present in the system.

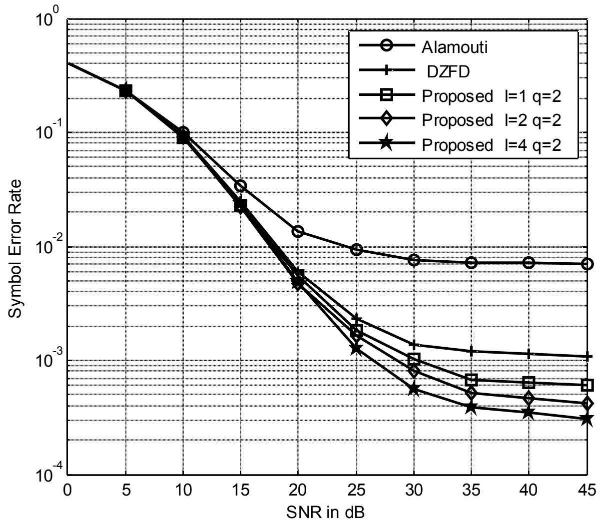

Fig.2 SER Vs SNR for different detection methods for normalized Doppler frequency of 0.06

The proposed interference cancellation scheme outperforms the conventional above detection methods as it cancels both the CCI and ICI effect jointly. It cancels the interferences in two steps. In the first step, the CCI effect is being cancelled by using DZFD method. In the second step it evaluates the ICI gain 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.

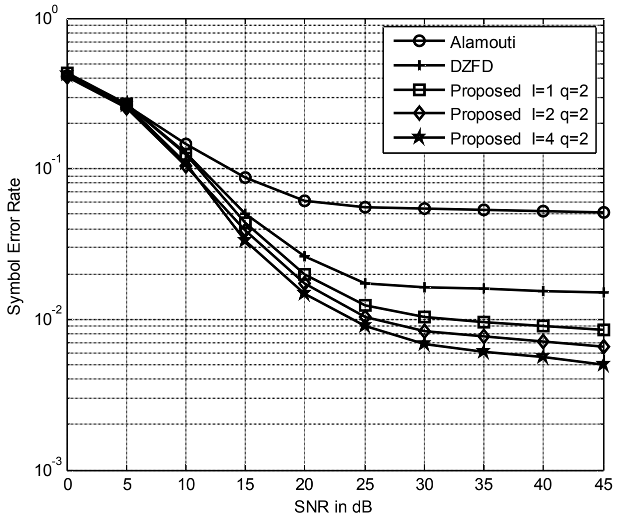

Fig.3 SER Vs SNR for different detection methods for normalized Doppler frequency of 0.12

V. CONLCUSION

The Alamouti coded STBC OFDM system undergoes two types of interference namely CCI and ICI in time varying fading channel. To mitigate the CCI effect, we have adopted the DZFD method and it performs better than Alamouti detection method but is not accurate enough as ICI effect is still present in the system. Hence, we have purposed an interference cancellation scheme which cancels the CCI 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 STBC OFDM system performance in highly mobile environment with less computational complexity.

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