Co-channel Interference Suppression Techniques for STBC OFDM System over Doubly Selective Channel

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Abstract— **The Alamouti Space Time Block Code (STBC) based Orthogonal Frequency Division Multiplexing (OFDM) is very attractive in frequency selective channel as the channels remain 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). 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, we propose a suboptimal MDF detection which provides comparable performance to that of ML with very less computational complexity. Finally, the performances of the above detection methods are compared in terms of symbol error rate (SER) and computational complexity for STBC OFDM system over doubly selective channel.**

Key Words — **STBC, OFDM, CCI, DETECTION**

I. INTRODUCTION

Now-a-days, most of the wireless communication system is focusing on reliability and spectral efficiency [1]-[2]. The link reliability is solved by STBC 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. 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 [6]. 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) [7]-[10]. The ICI occurs due to the loss of orthogonality among the subcarrier within the OFDM 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 [10]. Hence, we only consider the CCI effect on the Alamouti coded OFDM system.

In literature, various detection methods have been addressed for cancelling the effects of CCI. In [11], 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 diagonalized zero forcing detector (DZFD) is proposed in [12]. A successive interference cancellation (SIC) method is proposed in [5]. The decision feedback (DF) method is originally proposed in [13]. Then it is extended for STBC/SFBC OFDM system in [9]. The Maximum Likelihood (ML) detection method are addressed in [9],[12]. In this paper, we have analyzed the above detection methods and proposed a suboptimal modified DF (MDF) detection method to cancel the CCI effect

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 different detection techniques are presented in Section III along with the computational complexity. In Section IV, the performance of these detection methods are compared on the basis of SER. Finally, Section V concludes the paper.

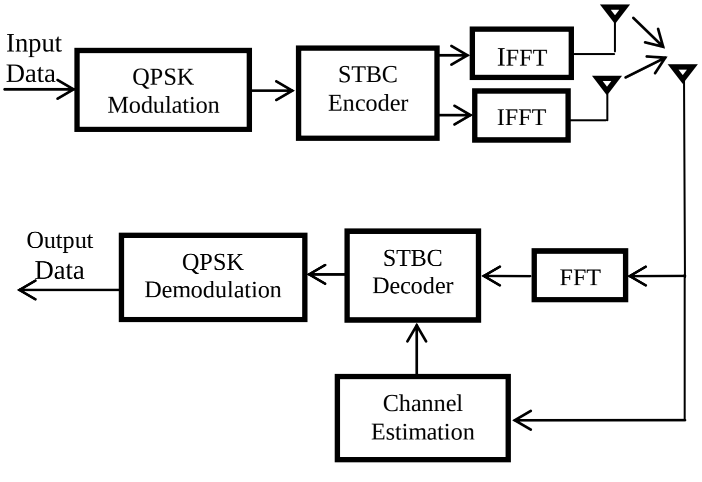

Fig.1 Block diagram of an STBC-OFDM system model

II. SYSTEM MODEL

In this section, an STBC based OFDM system with two transmit antennas and one receive antenna is described along with the exponential power delay profile and Jakes sum of sinusoidal (SOS) model as time varying 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 Fig1. 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 and is given as bellow

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

$$\text{where} \quad k = 0,1,2,\ldots\ldots\ldots N-1$$

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

Then, the encoded signal is 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 demodulated using Fast Fourier Transformation (FFT). The FFT output of the received signal after the removal of CP can be written in the matrix form and is given by

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

where $H_{1,t}(k)$ and $H_{2,t}(k)$ are the CFR for the first and second transmit antennas at the first time instant respectively. $Z_t(k)$ is the circularly complex zero mean additive white Gaussian noise after the FFT operation.

It is to be noted that the channel is taken to be ideal where it is assumed that the perfect channel knowledge is known at the receiver side. According to Alamouti scheme, the channels are considered to be static over two consecutive OFDM symbol block, i.e., $H_{1,\,t} = H_{1,\,t\,+\,T}$ and $H_{2,\,t} = H_{2,\,t\,+\,T}$. The STBC decoding operation is performed by multiplying H^H on both sides of (2), the original transmitted signal can be recovered after taking the hard decision of the decoded signal and can be written as

$$\hat{X}(k) = Q\left(\frac{\tilde{X}(k)}{\Phi(k)}\right) \qquad (3)$$

$$\text{where} \quad \tilde{X} = H^H(k)Y(k)$$

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

where

$\tilde{X}$ is the decoded signal and Q denotes the hard decesion 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 an orthogonal matrix and is given by

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

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

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

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

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

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

$\alpha_1(k)X_1(k)$ and $\alpha_2(k)X_2(k)$ are the desired signals. $\beta(k)X_2(k)$ and $\beta^*(k)X_1(k)$ are the CCI signals 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 for STBC OFDM in time selective channel.

B. Channel Model

In this paper, the wireless channel is assumed to be time varying frequency selective fading (Doubly selective) channel. The frequency selective channel is employed as exponential power delay profile (PDP) [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 channel can be expressed as

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

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

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

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

$$\sigma_l^2 = \sigma_0^2 \lambda^l. \tag{8}$$

Furthermore, each multipath is modeled as uncorrelated Rayleigh fading channel with Jakes sum-of-sinusoidal (SOS) model [15].

III. 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.

A. SIC Detection Method

The successive interference cancellation method is proposed in [10]. 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 (4). Hence the SIC detection method is based on this gain difference property to recover the original transmitted signal and is illustrated below

1. $\tilde{X}_1(k) = \alpha_1(k)X_1(k) + \beta(k)X_2(k) + Z'_t(k)$ (9)
2. $\tilde{X}_2(k) = \beta^*(k)X_1(k) + \alpha_2(k)X_2(k) + Z'_{t+T}(k)$ (10)
3. *if* $\alpha_1(k) > \alpha_2(k)$

$$\begin{aligned} \hat{X}_1(k) &= Q(\tilde{X}_1(k)/\alpha_1(k)) \\ \hat{X}_2(k) &= Q((\tilde{X}_2 - \beta^*(k)\hat{X}_1(k))/\alpha_2(k)) \end{aligned} \tag{11}$$

4. *else*

$$\begin{aligned} \hat{X}_2(k) &= Q(\tilde{X}_2(k)/\alpha_2(k)) \\ \hat{X}_1(k) &= Q((\tilde{X}_1 - \beta(k)\hat{X}_2(k))/\alpha_1(k)) \end{aligned} \tag{12}$$

B. 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 Ω is multiplied with the H matrix [11] and is given below

$$\Omega H = \mathrm{diag}(\varphi_1, \varphi_2) \tag{13}$$

where φ_1 and φ_2 are the complex number.

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

$$\Omega = \begin{bmatrix} H^*_{1,t+T}(k) & H_{2,t}(k) \\ H^*_{2,t+T}(k) & -H_{1,t}(k) \end{bmatrix} \tag{14}$$

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

$$\begin{aligned} \varphi &= \varphi_1 = \varphi_2 \\ &= H^*_{1,t+T}(k)\,H_{1,t}(k) + H_{2,t}(k)\,H^*_{2,t+T}(k) \end{aligned} \tag{15}$$

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

$$\tilde{X} = \Omega Y = \mathrm{diag}(\varphi, \varphi)X + \Omega Z \tag{16}$$

The estimated original transmitted signal can be obtained by dividing the value of φ on both side of (16) and then taking the hard decision

$$\hat{X}_1(k) = Q(\frac{\tilde{X}_1(k)}{\varphi(k)}) = X_1 + Z \tag{17}$$

$$\hat{X}_2(k) = Q(\frac{\tilde{X}_2(k)}{\varphi(k)}) = X_2 + Z \tag{18}$$

The DZFD detection method is simple as it simply forces the two CCI terms to zero.

C. DF Detection Method

The decision feedback (DF) detector was proposed for STBC-OFDM system in [9]. 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 $\hat{X}_1$ using DZFD detection method by using the (17).
2. Cancel the contribution of $\hat{X}_1$ by subtracting it from the mixed detected output signal in (9). Then take the hard decision to obtain the estimated signal. The estimated signal $\hat{X}_2$ can be written as

$$\hat{X}_2(k) = Q((\tilde{X}_2 - \beta^*(k)\hat{X}_1(k))/\alpha_2(k)) \tag{19}$$

D. Proposed Modified DF (MDF) Detection Method

In this paper, we have proposed a modified DF (MDF) detection to cancel the CCI effect. This method is the combination of SIC and DZFD method. The MDF method chooses the estimated signal coming from DZFD method based on gain diversity property and then cancel their contribution according to SIC method with some modification. The algorithm for MDF detection method is given below

1. *if* $\alpha_1(k) > \alpha_2(k)$

$$\hat{X}_1(k) = Q((\hat{X}_1(k)/\varphi) \tag{20}$$

$$\hat{X}_2(k) = Q((\tilde{X}_2 - \beta^*(k)\tilde{X}_1(k))/\alpha_2(k)) \tag{21}$$

$$\hat{X}_1(k) = Q((\tilde{X}_1 - \beta(k)\hat{X}_2(k))/\alpha_1(k)) \tag{22}$$

2. *else*

$$\hat{X}_2(k) = Q((\hat{X}_2(k)/\varphi) \tag{23}$$

$$\hat{X}_1(k) = Q((\tilde{X}_1 - \beta(k)\hat{X}_2(k))/\alpha_1(k)) \tag{24}$$

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

E. 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

$$\hat{X}(k) = \underset{X_1, X_1 \in C_M}{\arg\min} \left\| Y(k) - H(k)\begin{bmatrix} X_1 \\ X_2 \end{bmatrix} \right\|^2 \tag{26}$$

where C_M denotes the constellation points.

ML detection requires $|C_M|^2$ times matrices calculation to solve (23) in order to estimate the original transmitted signal in the receiver side. The ML detection performs the best among all the detection method but with the highest computational complexity ($|C_M|^2$ matrices calculation) and hence is not preferable from the hardware implementation perspective.

Table1.Computational Complexity

	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

F. Computational Complexity

To calculate the computational complexity, we consider only complex multiplication and divisions per subcarrier. Alamouti detection method involves 4 complex multiplications for $\tilde{X} = H^H Y$. In addition to that α_1 and α_2 involves 2 multiplication. $\tilde{X}_1/\alpha_1$ and $\tilde{X}_2/\alpha_2$ does not require any complexity as both α_1 and α_2 are scalar quantity. For SIC detection technique 4 complex multiplication are required for $\tilde{X}$ and α_1, α_2, β requires each two complex multiplication. $\beta^*\hat{X}_1$ and $\beta\hat{X}_2$ needs each one multiplication each. Division by α_1 and α_2 does not require any computational complexity. Therefore, total computational complexity involved in SIC method is 12. In DZFD, multiplying Ω with Y requires 4 complex multiplication and φ needs 2 complex multiplication. It is noted that one complex division require twice the number of complexity to complex multiplication. Hence, DZFD involves total 10 numbers of complex multiplications. DF detection technique needs 10 complex multiplication to estimate $\hat{X}$ using DZFD method, 4 complex multiplication for $H^H Y$ and 6 complex multiplication for β, α_1, α_2. Also one complex multiplication is required for $\beta^*\hat{X}_1$.The MDF involves same number of computational complexity to that DF with additional 3 complex multiplication i.e. 2 number of $\beta\hat{X}_2$ and one $\beta^*(k)\hat{X}_1$. Total number of computational complexity for MDF method is 24. The ML detection method involves $4(C_M)^2$ complex multiplications to solve (26). The computational complexity of various detection methods are summarized in Table 1.

IV. SIMULATION RESULTS

The performance comparison of different detection methods including Alamouti, SIC, DZFD, DF, MDF and ML methods for STBC based OFDM system are carried out on the basis of SER over various mobile speeds. The simulation parameters used for simulation are listed on the Table2.

Table2.Simulation Parameter

Parameter	**Value**
FFT Size	128
Number of Subcarrier	128
Number of CP	32
Data Modulation	QPSK
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	50/100/200 Km/h
Normalized Doppler frequency (F_dNTs)	0.03/0.06/0.12

The SER performances for SISO OFDM and STBC OFDM with different CCI cancellation techniques e.g. Alamouti, SIC, DZFD, DF, ML and MDF detectors for mobile speed 50Km/h (normalized Doppler frequency $F_dNT_s = 0.03$) is shown in the Fig.2. 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 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. The DF gives better result than Alamouti, SIC and DZFD methods. 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 1. From the table, it is seen that ML method has the highest whereas Alamouti method has the least computational complexity followed by DZFD, DF and MDF. We also see that MDF method achieves results comparable to the ML method with lesser computational complexity

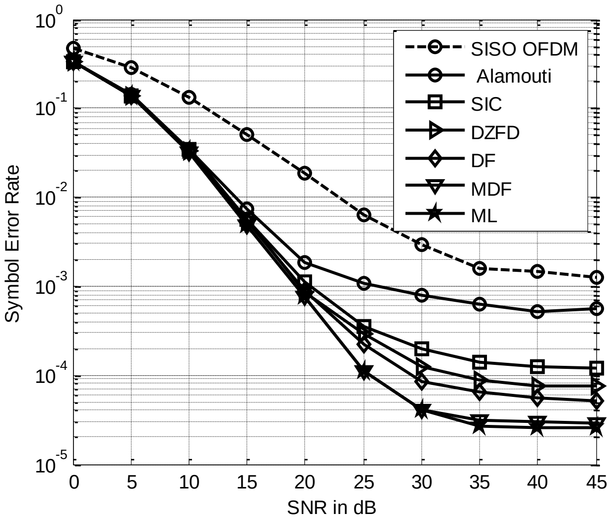

Fig.2 SER Vs SNR for different detection methods for normalized doppler frequency of 0.03

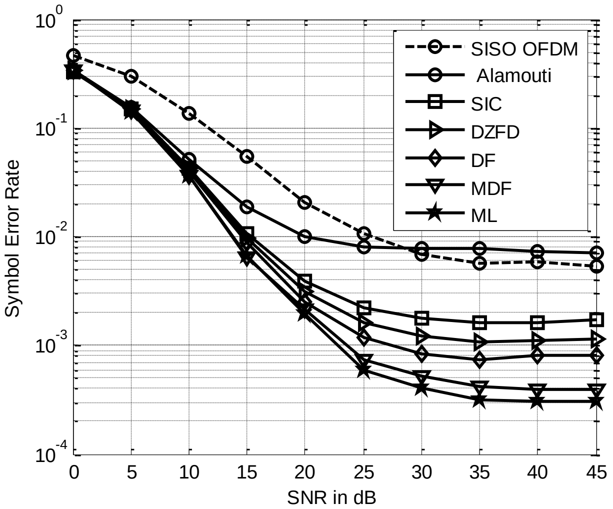

Fig.3 SER Vs SNR for different detection methods for normalized doppler frequency of 0.06

Fig.3 and Fig.4 show the SER performance of various detection methods for normalized Doppler frequency of 0.06 and 0.12 respectively. The simulation results show that as the normalized Doppler spread increases the Alamouti STBC OFDM becomes worse than SISO OFDM at high end of the SNR. From the Fig.2-Fig.4, we have seen that, the performance of all the detection methods decreases drastically with increase in vehicle speed. The performance of different detection methods in the descending order are given as follows: ML, MDF, DF, DZFD, SIC and Alamouti.

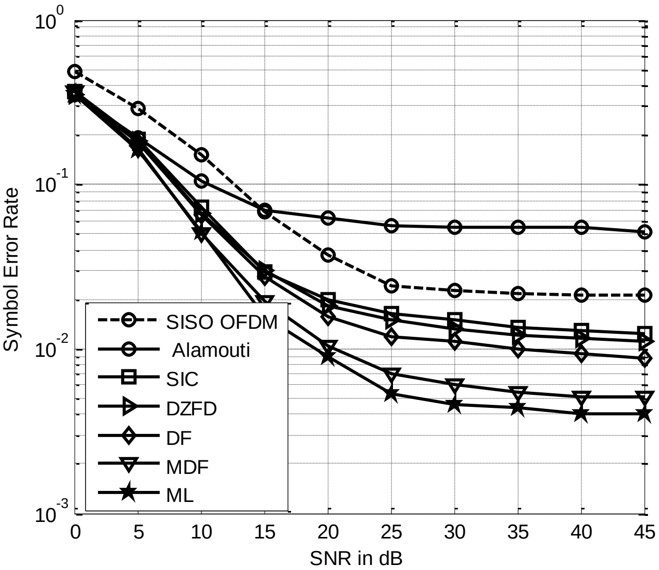

Fig.4. SER Vs SNR for different detection methods for normalized doppler frequency 0.12

V. CONLCUSIONS

In this paper, we have analyzed various detection methods to suppress the effects of CCI for STBC OFDM system over doubly selective channel and proposed a MDF detection technique. The various detection techniques which include Alamouti, SIC, DZFD, DF, ML and the proposed MDF method are compared in terms of SER and computational complexity. From the simulation results, it is seen that the proposed MDF method achieves comparable performance to the ML method with a lesser computational complexity.

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