Iterative Block Decision Feedback Equalizer for Time-Frequency Interleave Diversity Scheme

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***Abstract*—The time-frequency interleave (TFI) diversity scheme for single carrier block transmission with frequency domain equalization (SC-FDE) has been proposed. For single antenna wireless communication systems, it can provide frequency diversity in frequency selective channels by interleaving and retransmitting. In this article, the iterative block decision feedback equalization (IBDFE) structure for TFI diversity scheme is proposed. Both the feed-forward filter (FFF) and feed-backward filter (FBF) work in the frequency domain, which makes the implementation complexity low. The FFF and FBF coefficients based on minimum mean square error (MMSE) criterion are derived. The correlation between the transmitted symbols and the detected symbols are estimated in a simple iterative manner. Simulation results show that for TFI diversity scheme with IBDFE, a much better bit error rate (BER) performance can be obtained than TFI with frequency domain linear equalizer (FD-LE) only for one more iteration. Compared to IBDFE without TFI diversity, the performance gain is impressive.**

***Index Terms*—TFI, IBDFE, diversity**

I. INTRODUCTION

Broadband wireless communications for high-speed data transmission has been tremendously demanded in recent years. However, the frequency-selective multipath fading severely degrades the bit error rate (BER) performance. Single carrier block transmission with frequency domain equalization (SC-FDE), where data is transmitted block by block in the time domain while equalization is carried out in the frequency domain, has been shown to be attractive. Compared to orthogonal frequency division multiplexing (OFDM), SC-FDE has similar performance and essentially same overall implementation complexity but lower peak-to-average power ratio (PARR) and less sensitivity to carrier frequency offsets [1]. In addition, in severe frequency selective channels, SC-FDE has much less computational complexity and better convergence prosperities to achieve the same or better performance than time domain equalization [1][2].

Diversity is one of the most direct and effective way to combat fading channels [3]. However, for a system whose terminals are constrained by size and power, diversity techniques with multiple antennas are not practical. In [4], we have proposed a time-frequency interleave (TFI) block transmission structure for SC-FDE and it can provide frequency diversity for single-input single-output (SISO) wireless communication systems. The information blocks are interleaved and retransmitted. Benefit from the elaborate design of the interleave matrix, the interleave operation is carried out in the time domain and it leads to equivalent interleave in the frequency domain. By interleaving and retransmitting, frequency domain symbols carrying the same information experience relatively independent fading, which means frequency diversity.

For single carrier block transmission systems, there exits a variety of equalization structures. Frequency domain linear equalizer (FD-LE) based on zero forcing (ZF) or minimum mean square error (MMSE) criterion [5] is low complexity. However, the noise enhancement problem significantly degrades the BER performance of FD-LE. The hybrid time-frequency domain decision feedback equalization (DFE) structure, which uses a FD-LE as a feed-forward equalizer and a conventional time-domain (TD) transversal filter as a feedback equalizer, can obtain a better BER performance [1]. However, the implementation complexity is quite high. In [6], a frequency-domain iterative block decision feedback equalizer (IBDFE) is proposed. Both the feed-forward and feed-backward filters operate in the frequency domain and it leads to low implementation complexity and better BER performance. In this article, the IBDFE structure for TFI diversity scheme is proposed. The feed-forward filter (FFF) and feed-backward filter (FBF) coefficients based on MMSE criterion are derived. The correlation between the transmitted data and the detected data at each iteration is calculated in an iterative manner. Simulation results show that with TFI block transmission and the proposed IBDFE diversity receiving, an impressive BER performance can be obtained.

This paper is organized as following, we present the TFI-IBDFE structure in section II. In section III, the FFF and FBF coefficients based on MMSE criterion are derived. In section IV, we present a simple iterative way to estimate the correlation parameters. In section V, the simulation results are presented. Finally, section VI concludes this paper.

Notation: $(\cdot)^T$, $(\cdot)^H$ and $(\cdot)^{-1}$ denote matrix/vector transpose, Hermitian transpose and matrix inverse, respectively. We use $\boldsymbol{I}_N$ for a $N \times N$ identity matrix. $\mathbf{1}_N$ and $\mathbf{0}_N$ denote a $N \times 1$ all-one vector and a $N \times 1$ all-zero vector, respectively. Moreover, $(\cdot)[i, j]$ denotes the *(i,j)*th entry of a matrix and $(\cdot)[k]$ denotes the *k*th element of a vector. When operating on a matrix, $diag(\cdot)$ denotes a column vector formed from the diagonal of the matrix. When operating on a vector, $diag(\cdot)$ denotes a diagonal matrix with the elements of the vector on

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the diagonal.

II. System Model

We consider the cyclic prefixed (CP) single carrier block transmission in quasi-static block-fading channels. For TFI block transmission with diversity order R, each input information block $\boldsymbol{d}$ is repeated for R times. We call the input block $\boldsymbol{d}$ information block and the output R blocks TFI repetition block. The first TFI repetition block $\boldsymbol{d}_0 = \boldsymbol{d}$ is the same as the input information block. By reorganizing the order of each element in the prior TFI repetition block, the rth ($0 < r < R$) TFI repetition block is given by

$$\boldsymbol{d}_r = \boldsymbol{A}\boldsymbol{d}_{r-1} = \boldsymbol{A}^r\boldsymbol{d}_0 = \boldsymbol{A}^r\boldsymbol{d} \tag{1}$$

where $\boldsymbol{A}$ is the interleaving matrix which is a permutation and g-circulant matrix satisfying that for $i = 0, 1, \cdots, N-1$,

$$\boldsymbol{A}[i,j] = \begin{cases} 1, & j = \mathrm{mod}(g * i, N) \\ 0, & otherwise \end{cases} \tag{2}$$

where $\mathrm{mod}(a, b)$ represents the modulus operation [4]. g is an integer which is prime to the block length N. In order to let frequency domain signals carrying the same information experience independent fading, g should be lager than the coherent bandwidth. The frame structure is shown in Fig. 1.

Due to the special architecture of the $N \times N$ matrix $\boldsymbol{A}$, it has the following properties [4]:

$$\boldsymbol{A}\boldsymbol{A}^T = \boldsymbol{A}^T\boldsymbol{A} = \boldsymbol{I}_N$$

$$\boldsymbol{F}\boldsymbol{A}\boldsymbol{F}^{-1} = \boldsymbol{A}^T$$

$$diag(\boldsymbol{A}\Sigma\boldsymbol{A}^T) = \boldsymbol{A}diag(\Sigma)$$

where $\boldsymbol{F}$ is the $N \times N$ DFT matrix with the *(i,j)*th entry as $\boldsymbol{F}[i,j] = \exp(-j\frac{2\pi}{N}ij)$. Σ is an arbitrary diagonal matrix. In addition, $\boldsymbol{A}^r$ has the same properties as $\boldsymbol{A}$.

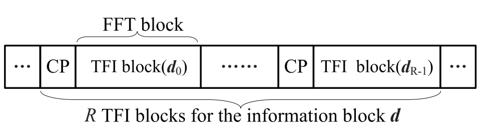

Fig. 1. Frame structure of TFI diversity scheme

According to the properties of the interleaving matrix $\boldsymbol{A}$, the frequency domain transmitted TFI repetition block can be expressed as

$$\begin{aligned} \boldsymbol{X}_r &= \boldsymbol{F}\boldsymbol{d}_r \\ &= \boldsymbol{F}\boldsymbol{A}\boldsymbol{d}_{r-1} \\ &= (\boldsymbol{F}\boldsymbol{A}\boldsymbol{F}^{-1})\boldsymbol{F}\boldsymbol{d}_{r-1} \\ &= \boldsymbol{A}^T\boldsymbol{X}_{r-1} \\ &= (\boldsymbol{A}^r)^T\boldsymbol{X}_0 \\ &= (\boldsymbol{A}^r)^T\boldsymbol{X} \end{aligned} \tag{3}$$

where $\boldsymbol{X}_{r-1} = \boldsymbol{F}\boldsymbol{d}_{r-1}$, $\boldsymbol{X}_0 = \boldsymbol{F}\boldsymbol{d}_0$, $\boldsymbol{X} = \boldsymbol{F}\boldsymbol{d}$. Following $\boldsymbol{A}\boldsymbol{A}^T = \boldsymbol{I}_N$, it leads to

$$\boldsymbol{X}_0 = \boldsymbol{A}^r\boldsymbol{X}_r \tag{4}$$

From (1)(3)(4), we can see that the information block $\boldsymbol{d}$ is interleaved in the time and frequency domain simultaneously. The interleaver in the time domain is equivalent to the deinterleaver in the frequency domain. Due to the interleaving in the frequency domain and retransmitting, R frequency domain symbols carrying the same information will experience relatively independent fading, which means diversity. By diversity receiving at the receiver, more reliable detection can be achieved.

After interleaving, CP is added to each of the R TFI repetition blocks. Then the series of transmit pulse shapes is transmitted over the frequency selective channel. The transmitter structure is shown in Fig. 2.

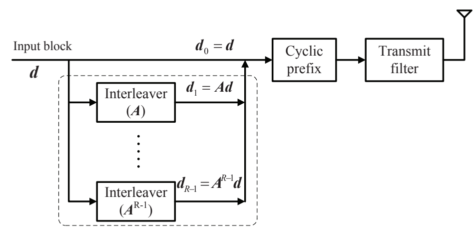

Fig. 2. Transmitter structure of TFI diversity scheme

At the receiver, the received waveforms are passed through the receive filter. After sampling the receive filter output, CP is removed for each of the R received TFI repetition blocks. Assume that the channel impulse response (CIR) is of order L with taps $\boldsymbol{h} = [h[0], h[1], \cdots, h[L-1]]^T$. If the CIR varies for each TFI repetition block duration, the varying CIR provides diversity itself, even without interleaving. We consider the case where the CIR remains unchanged over the R TFI repetition blocks for each information block. Then the received rth TFI repetition block can be expressed as

$$\boldsymbol{y}_r = \boldsymbol{C}\boldsymbol{d}_r + \boldsymbol{v}_r \tag{5}$$

where

$$\boldsymbol{C} = \begin{bmatrix} h_0 & 0 & \cdot & 0 & h_{L-1} & h_{L-2} & \cdot & h_1 \\ h_1 & h_0 & 0 & \cdot & 0 & h_{L-1} & \cdot & h_2 \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ 0 & \cdot & 0 & h_{L-1} & h_{L-2} & \cdot & h_1 & h_0 \end{bmatrix}$$

is a circulant Toeplitz matrix with the first column being $\boldsymbol{h}$ zero-padded to length N [7]. $\boldsymbol{v}_r$ is the noise vector with each element independent and identically distributed (i.i.d.) Gaussian random variable. It is known that the circulant Toeplitz $\boldsymbol{C}$ can be decomposed as

$$\boldsymbol{C} = \boldsymbol{F}^{-1}\Lambda\boldsymbol{F} \tag{6}$$

where Λ is a diagonal matrix with the *(k,k)*th entry as $H_0[k]$, where $H_0[k]$ is the kth DFT coefficient of $\boldsymbol{h}$ zero-padded to length N. Let $\boldsymbol{H}_0 = [H_0[0], H_0[1], \cdots, H_0[N-1]]^T$. By DFT, the frequency domain received TFI repetition block can be expressed as

$$\begin{aligned} \boldsymbol{Y}_r &= \boldsymbol{F}\boldsymbol{y}_r \\ &= \Lambda\boldsymbol{F}\boldsymbol{d}_r + \boldsymbol{F}\boldsymbol{v}_r \\ &= \Lambda(\boldsymbol{A}^r)^T\boldsymbol{X} + \boldsymbol{V}_r \end{aligned} \tag{7}$$

where $\boldsymbol{V}_r = \boldsymbol{F}\boldsymbol{v}_r$. By deinterleaving in the frequency domain, we have

$$\begin{aligned}\boldsymbol{Z}_r &= \boldsymbol{A}^r\boldsymbol{Y}_r \\ &= \boldsymbol{A}^r\Lambda(\boldsymbol{A}^r)^T\boldsymbol{X} + \boldsymbol{A}^r\boldsymbol{V}_r \\ &= \Lambda_r\boldsymbol{X} + \boldsymbol{A}^r\boldsymbol{V}_r\end{aligned} \tag{8}$$

where $\Lambda_r = \boldsymbol{A}^r\Lambda(\boldsymbol{A}^r)^T$. According to the third property of $\boldsymbol{A}$, Λ_r is also a diagonal matrix. Let $\boldsymbol{H}_r = diag(\Lambda_r)$, we have

$$\boldsymbol{H}_r = \boldsymbol{A}^r diag(\Lambda) = \boldsymbol{A}^r\boldsymbol{H}_0 \tag{9}$$

and the kth element can be expressed as

$$H_r\left[k\right] = H_0\left[\bmod(k * g^r, N)\right] \tag{10}$$

As $\boldsymbol{A}^r$ is a permutation matrix and the noise are independent and identically distributed, in the rest of the article, we still use $\boldsymbol{V}_r$ to represent $\boldsymbol{A}^r\boldsymbol{V}_r$. The kth element of $\boldsymbol{Z}_r$ can be expressed as

$$Z_r[k] = H_r[k]X[k] + V_r[k] \tag{11}$$

The IBDFE structure for TFI block transmission is shown in Fig. 3. The frequency domain equalized data at the lth iteration can be expressed as

$$\begin{aligned}Q^{(l)}\left[k\right] &= \left(\sum_{r=0}^{R-1} W_r^{(l)}\left[k\right]Z_r\left[k\right]\right) + B^{(l)}\left[k\right]\hat{X}^{(l-1)}\left[k\right] \\ &= \left(\sum_{r=0}^{R-1} W_r^{(l)}\left[k\right]H_r\left[k\right]\right)X\left[k\right] + B^{(l)}\left[k\right]\hat{X}^{(l-1)}\left[k\right] \\ &+ \left(\sum_{r=0}^{R-1} W_r^{(l)}\left[k\right]V_r\left[k\right]\right)\end{aligned} \tag{12}$$

where $W_r^{(l)}[k]$ and $B^{(l)}[k]$ are the FFF and FBF coefficients at the lth iteration [6].

III. MMSE EQUALIZATION COEFFICIENTS

Here we consider the FFF and FBF coefficients based on MMSE criterion. We assume that the information symbols of $\boldsymbol{d}$ are independent and identically distributed with zero mean and statistically independent of the noise. From Fig. 3, the mean square error (MSE) at the lth iteration can be expressed as

$$\varepsilon_l = \frac{1}{N}E\left[(\boldsymbol{q}^{(l)} - \boldsymbol{d})^H(\boldsymbol{q}^{(l)} - \boldsymbol{d})\right] \tag{13}$$

where $\boldsymbol{q}^{(l)} = \left[q^{(l)}[0], q^{(l)}[1], \cdots, q^{(l)}[N-1]\right]^T$ represents the time domain equalized information block. By applying the Parseval's theorem, we have

$$\varepsilon_l = \frac{1}{N^2}E\left[(\boldsymbol{Q}^{(l)} - \boldsymbol{X})^H(\boldsymbol{Q}^{(l)} - \boldsymbol{X})\right] \tag{14}$$

where $\boldsymbol{Q}^{(l)} = \left[Q^{(l)}[0], Q^{(l)}[1], \cdots, Q^{(l)}[N-1]\right]^T$ is the frequency domain equalized information block. Our goal is to minimize (14). For convenience, let

$$\hat{\boldsymbol{X}}^{(l-1)} = \left[\hat{X}^{(l-1)}[0], \hat{X}^{(l-1)}[1], \cdots, \hat{X}^{(l-1)}[N-1]\right]^T$$

$$\boldsymbol{B}_l = \left[B^{(l)}[0], B^{(l)}[1], \cdots, B^{(l)}[N-1]\right]^T$$

$$\boldsymbol{W}_r^{(l)} = \left[W_r^{(l)}[0], W_r^{(l)}[1], \cdots, W_r^{(l)}[N-1]\right]^T$$

$$\begin{aligned}\boldsymbol{W}_l = \Big[&W_0^{(l)}[0], \cdots, W_{R-1}^{(l)}[0], \cdots, \\ &W_0^{(l)}[R-1], \cdots, W_{R-1}^{(l)}[R-1]\Big]^T\end{aligned}$$

Obviously $\boldsymbol{B}_l$ represents the FBF coefficients vector at the lth iteration. $\boldsymbol{W}_r^{(l)}$ represents the FFF coefficients vector at the lth iteration for the received rth TFI repetition block and $\boldsymbol{W}_l$ is a vector of all FFF coefficients at the lth iteration. Our job is to obtain $\boldsymbol{W}_l$ and $\boldsymbol{B}_l$ which can minimize the MSE. We define some matrices and vectors as following,

$$\Lambda_x = diag(\boldsymbol{X})$$

$$\Lambda_{(l-1)} = diag\left(\hat{\boldsymbol{X}}^{(l-1)}\right)$$

Define the $N \times NR$ matrices Λ_h and $\boldsymbol{V}$ as

$$\Lambda_h[i,j] = \begin{cases} H_{j-iR}[i], & iR \le j \le (i+1)R-1 \\ 0, & otherwise \end{cases} \tag{15}$$

$$V[i,j] = \begin{cases} V_{j-iR}[i], & iR \le j \le (i+1)R-1 \\ 0, & otherwise \end{cases} \tag{16}$$

Then we let

$$\boldsymbol{H}_x = \Lambda_x\Lambda_h$$

$$\boldsymbol{H}_{xx} = \Lambda_h^H\Lambda_h$$

$$\Gamma_h = \Lambda_h^T\boldsymbol{1}_N$$

Let $\rho_l = [\rho_l[0], \rho_l[1], \cdots, \rho_l[N-1]]^T$ and $\Omega_l = diag(\rho_l)$, where

$$\rho_l[k] = E\left\{X[k]\hat{X}^{(l)*}[k]\right\} \tag{17}$$

represents the correlation between the frequency domain transmitted data and detected data at the lth iteration. From Fig. 3 and the matrices we defined, the frequency domain equalized information block $\boldsymbol{Q}^{(l)}$ can be expressed as

$$\boldsymbol{Q}^{(l)} = (\boldsymbol{H}_x + \boldsymbol{V})\boldsymbol{W}_l + \Lambda_{(l-1)}\boldsymbol{B}_l \tag{18}$$

As the information symbols are statistically independent of the noise, substitute (18) into (14),

$$\begin{aligned}\xi_l &= N^2\varepsilon_l \\ &= \boldsymbol{W}_l^H E\left[\boldsymbol{H}_x^H\boldsymbol{H}_x\right]\boldsymbol{W}_l + \boldsymbol{W}_l^H E\left[\boldsymbol{H}_x^H\Lambda_{(l-1)}\right]\boldsymbol{B}_l \\ &- \boldsymbol{W}_l^H E\left[\boldsymbol{H}_x^H\boldsymbol{X}\right] + \boldsymbol{W}_l^H E\left[\boldsymbol{V}^H\boldsymbol{V}\right]\boldsymbol{W}_l \\ &+ \boldsymbol{B}_l^H E\left[\Lambda_{(l-1)}^H\boldsymbol{H}_x\right]\boldsymbol{W}_l + \boldsymbol{B}_l^H E\left[\Lambda_{(l-1)}^H\Lambda_{(l-1)}\right]\boldsymbol{B}_l \\ &- \boldsymbol{B}_l^H E\left[\Lambda_{(l-1)}^H\boldsymbol{X}\right] - E\left[\boldsymbol{X}^H\boldsymbol{H}_x\right]\boldsymbol{W}_l \\ &- E\left[\boldsymbol{X}^H\Lambda_{(l-1)}\right]\boldsymbol{B}_l + E\left[\boldsymbol{X}^H\boldsymbol{X}\right]\end{aligned} \tag{19}$$

Let p and σ^2 represent the frequency domain signal power and noise power, respectively. Since we consider the information symbols to be i.i.d. with zero mean, $E\left\{X\left[i\right]X^*\left[j\right]\right\} = E\left\{\hat{X}^{(l)}\left[i\right]\hat{X}^{(l)*}\left[j\right]\right\} = p\delta_{ij}$ and it leads to the following results:

$$E\left[\boldsymbol{H}_x^H\boldsymbol{H}_x\right] = E\left[\Lambda_h^H\Lambda_x^H\Lambda_x\Lambda_h\right] = p\boldsymbol{H}_{xx}$$

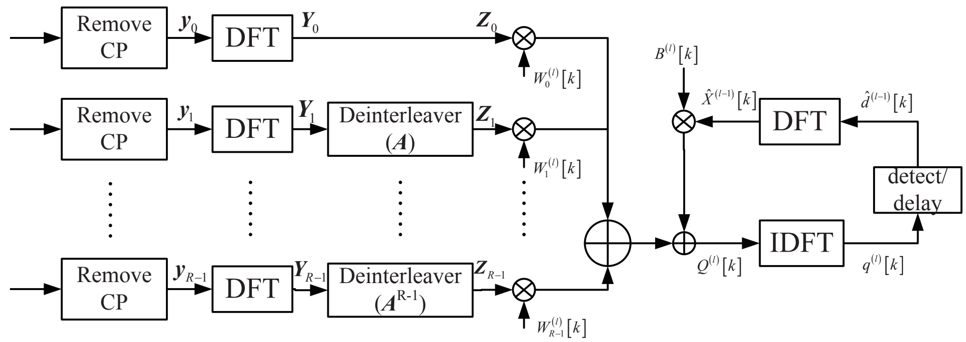

Fig. 3. IBDFE structure of TFI diversity scheme

$$E\left[\Lambda_{(l-1)}^{H}\boldsymbol{H}_x\right]=E\left[\Lambda_{(l-1)}^{H}\Lambda_x\Lambda_h\right]=\Omega_{l-1}\Lambda_h$$
$$E\left[\boldsymbol{H}_x^H\boldsymbol{X}\right]=E\left[\Lambda_h^H\Lambda_x^H\boldsymbol{X}\right]=p\Gamma_h^*$$
$$E\left[\Lambda_{(l-1)}^{H}\Lambda_{(l-1)}\right]=p\boldsymbol{I}_N$$
$$E\left[\Lambda_{(l-1)}^{H}\boldsymbol{X}\right]=\rho_{(l-1)}$$
$$E\left[\boldsymbol{V}^H\boldsymbol{V}\right]=\sigma^2\boldsymbol{I}_{NR}$$
$$E\left[\boldsymbol{X}^H\boldsymbol{X}\right]=Np$$

In order to minimize the MSE shown in (19), we also impose the constraint that the feed-backward filter removes pre- and postcursors, but doesn't remove the desired component [6], i.e.,

$$\sum_{k=0}^{N-1}B^{(l)}[k]=0$$

which can be written in a vector form as

$$\boldsymbol{B}_l^H\mathbf{1}_N=\mathbf{1}_N^T\boldsymbol{B}_l=0$$

By applying the Lagrange multiplier method, we derive the aim function

$$J_l=\xi_l+\lambda_l\boldsymbol{B}_l^H\mathbf{1}_N \tag{20}$$

where λ_l is the Lagrange multiplier at the lth iteration. By setting to zero the gradient of (20) with respect to $\boldsymbol{W}_l^*$, $\boldsymbol{B}_l^*$ and λ_l respectively, we derive

$$\frac{\partial J_l}{\partial \boldsymbol{W}_l^*}=\left(p\boldsymbol{H}_{xx}+\sigma^2\boldsymbol{I}_{NR}\right)\boldsymbol{W}_l+\Lambda_h^H\Omega_{l-1}^H\boldsymbol{B}_l-p\Gamma_h^*=0 \tag{21}$$

$$\frac{\partial J_l}{\partial \boldsymbol{B}_l^*}=\Omega_{l-1}\Lambda_h\boldsymbol{W}_l+p\boldsymbol{B}_l-\rho_{(l-1)}+\lambda_l\mathbf{1}_N=0 \tag{22}$$

$$\frac{\partial J_l}{\partial \lambda_l}=\boldsymbol{B}^H\mathbf{1}_N=0 \tag{23}$$

Combine (21), (22), (23), we derive

$$\lambda_l=\frac{\frac{\sigma^2}{p}\mathbf{1}_N^T\Omega_{l-1}\Psi\mathbf{1}_N}{\mathbf{1}_N^T\left(\Lambda_h\Lambda_h^H+\frac{\sigma^2}{p}I_N\right)\Psi\mathbf{1}_N} \tag{24}$$

$$\boldsymbol{W}_l=\Lambda_h^H\left[\boldsymbol{I}_N-\frac{1}{p^2}\Omega_{l-1}^H\Omega_{l-1}+\frac{\lambda_l}{p^2}\Omega_{l-1}^H\right]\Psi\mathbf{1}_N \tag{25}$$

$$\boldsymbol{B}_l=\frac{1}{p}\left(\rho_{(l-1)}-\Omega_{l-1}\Lambda_h\boldsymbol{W}_l-\lambda_l\mathbf{1}_N\right) \tag{26}$$

where

$$\Psi=\left[\Lambda_h\Lambda_h^H\left(\boldsymbol{I}_N-\frac{1}{p^2}\Omega_{l-1}^H\Omega_{l-1}\right)+\frac{\sigma^2}{p}\boldsymbol{I}_N\right]^{-1} \tag{27}$$

From (15), we can see that $\Lambda_h\Lambda_h^H$ is a diagonal matrix with the *(k,k)*th entry as $\sum\limits_{r=0}^{R-1}\left|H_r[k]\right|^2$. Obviously $\Omega_{l-1}^H\Omega_{l-1}$ is also a diagonal matrix with the *(k,k)*th entry as $\left|\rho_{(l-1)}[k]\right|^2$. Thus Ψ is also a diagonal matrix and there is no need for matrix inverse operation. Observe (24)–(27), the FFF coefficients vector $\boldsymbol{W}_l$ and FBF coefficients vector $\boldsymbol{B}_l$ can be derived with low implementation complexity.

IV. PARAMETER ESTIMATION

We consider the situation where the receiver has perfect channel state information (CSI). From (24)–(27), we can see that the only parameter unknown is $\rho_{(l-1)}$, i.e., the correlation between the frequency domain transmitted data and detected data at each iteration. According to the definition of $\rho_l[k]$, assume that $\boldsymbol{Q}^{(l)}-\hat{\boldsymbol{X}}^{(l)}$ is addictive white Gaussian noise, then

$$\begin{aligned}\rho_l&=E\left[\Lambda_x\hat{\boldsymbol{X}}^{(l)*}\right]\\&=E\left[\Lambda_x\boldsymbol{Q}^{(l)*}\right]\\&=E[\Lambda_x\boldsymbol{H}_x^*]\boldsymbol{W}_l^*+E[\Lambda_x\Lambda_{(l-1)}^*]\boldsymbol{B}_l^*\\&=p\Lambda_h^*\boldsymbol{W}_l^*+\Omega_{(l-1)}\boldsymbol{B}_l^*\end{aligned} \tag{28}$$

i.e., the correlation vector can be obtained in an iterative manner. For the first iteration, we have $\rho_0=\boldsymbol{0}_N$, which leads to $\lambda_1=0$, $\boldsymbol{B}_1=\boldsymbol{0}_N$, and

$$\begin{aligned}\boldsymbol{W}_1&=\Lambda_h^H\Psi\mathbf{1}_N\\&=\Lambda_h^H\left[\Lambda_h\Lambda_h^H+\frac{\sigma^2}{p}\boldsymbol{I}_N\right]^{-1}\mathbf{1}_N\end{aligned}$$

i.e.

$$W_r^1[k]=\frac{H_r^*[k]}{\sigma^2/p+\sum\limits_{u=0}^{R-1}\left|H_u[k]\right|^2}$$

which is equal to MMSE linear equalization without feedback.

At the lth iteration, based on $\rho_{(l-1)}$, the FFF coefficients vector $\boldsymbol{W}_l$ and the FBF coefficients vector $\boldsymbol{B}_l$ are derived according to (25), (26). Then $\rho_{(l)}$ can be refreshed according to (28) based on the newly derived $\boldsymbol{W}_l$ and $\boldsymbol{B}_l$.

V. Simulation Results

The BER performance of the proposed TFI diversity scheme with IBDFE is simulated. We consider frequency-selective Rayleigh block fading channels with an exponential power delay profile. The channel is assumed to be unchanged for each R TFI repetition blocks duration. The channel order is set to be $L = 8$. The data block length and the CP length are set to be $N = 128$ and $L_{CP} = 16$, respectively. A quaternary phase-shift keying (QPSK) is adapted. 100 channel realizations are generated and the BER is averaged.

Fig. 4 depicts the average BER performance of traditional IBDFE without diversity and TFI diversity scheme with IBDFE. Diversity order $R = 2$ is adapted for TFI diversity scheme. The interleave step is set to be $g = 19$. For both systems, the first two iterations yield a significant performance gain, while further iterations brings much less gain. For TFI block transmission with diversity order $R = 2$, the performance gain is about 4dB at BER $= 10^{-4}$ compared to traditional IBDFE without diversity. Compared to MMSE linear equalizer, which equals to one iteration IBDFE, IBDFE can obtain about 1dB performance gain for only one more iteration.

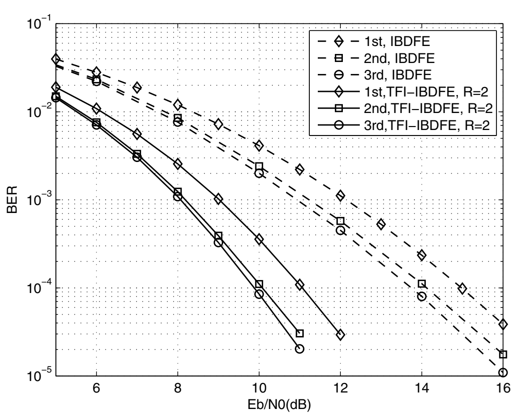

Fig. 4. Average BER performance comparison

VI. Conclusion

We propose the frequency domain IBDFE structure for TFI block transmission diversity scheme. The feed-forward and feed-backward filter coefficients based on MMSE criterion are derived. The correlation between the transmitted data and the detected data is estimated in an iterative manner. Simulation results show that for TFI block transmission diversity scheme with IBDFE, a better BER performance can be obtained than TFI with MMSE linear equalization in low implementation complexity sacrifice. Compared to traditional IBDFE without TFI diversity scheme, the BER performance gain is impressive.

Acknowledgment

This research is supported by the National Science and Technology Major Project No. 2011ZX03004-001-01, National Nature Science Foundation of China No. 60972019 and No. 61021001.

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