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SINGLE-CARRIER ZF FREQUENCY-DOMAIN EQUALIZATION FOR SPACE FREQUENCY BLOCK-CODED TRANSMISSIONS OVER FREQUENCY-SELECTIVE FADING CHANNELS

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ABSTRACT: This paper presents an Alamouti-like scheme for combining space–frequency block-coding (SFBC) with single-carrier frequency-domain equalization (SC-FDE) in wireless fading channels where channel response is not same for adjacent subcarriers. The matched filter at the receiver produces error floor in the bit error rate performance, which is compensated by the proposed design. This paper focuses on the design of low complexity zero forcing (ZF) equalizer for the combining receiver for a communication system with two transmit antennas and one receive antenna. It is shown, through computer simulations that the proposed design of the equalizer outperforms the matched filter receiver for fast fading mobile environments, and also provides an advantage of lower computational complexity at the receiver than classical ZF equalizer.
Keywords: Single-carrier frequency-domain equalization (SC-FDE), space-frequency block-code (SFBC), cyclic prefix (CP), zero forcing equalizer (ZF).

I. INTRODUCTION

In a single-carrier communication system, the equalization can be done either in the time domain or in the frequency domain [1, 2]. Single-carrier frequency-domain equalization (SC-FDE) [3-5] is an attractive equalization scheme for broadband wireless fading channels which are given by their lengthened impulse response memory. Under these conditions, single-carrier zero forcing frequency-domain equalization (SC ZF-FDE) has lower complexity, due to its use of the computationally-efficient fast Fourier transform (FFT), than time-domain equalization whose complexity increases with channel memory and spectral efficiency (trellis-based schemes) as it requires very long FIR filters. The SC-FDE as shown in [6] offers two main advantages over orthogonal frequency division multiplexing (OFDM); reduced sensitivity to carrier frequency errors and lower peak-to-average power ratio (PAPR). OFDM is prone to intrinsic problems of nonlinear distortion and carrier synchronization, which can be eliminated or suppressed with SC-FDE, as these are similar in performance and structure. The desired gain at the receiver can be achieved by transmitting the data from multiple transmit antennas or receiving at multiple receive antennas, without the burden of extra computational complexity. Alamouti [7] proposed a two transmit antenna diversity technique which achieves full diversity at full transmission rate, without requiring channel state information at the receiver and simple linear processing for maximum likelihood decoding. The Alamouti STBC scheme for fading environments has been captured with time-domain equalization [8]. The benefits of STBC and SC-FDE were combined [9] for slowly varying channels, where the channel response is assumed to be constant for two consecutive symbols [10, 11]. However, in practical scenarios, a high speed mobile causes fast fading which is characterized by different channel response for consecutive symbols. In order to suppress the effects of fast fading in wireless mobile environment, an SFBC SC-FDE scheme is proposed. The effectiveness of mitigating the fast fading distortion in frequency non-selective fading environment lies under SFBC as it utilizes two adjacent subcarriers over two transmit antennas [5], [8], unlike STBC which uses two adjacent time intervals. OFDM system can also be coded with SFBC to achieve high symbol error rate performance [9]. As the transmit sequence of an SC system is processed in time domain, so it is not relevant to directly apply SFBC to SC system [12]. In order to avail spatial as well as frequency diversities at the transmitter, the proposed combining receiver is derived under a low complexity ZF criterion.

II. PROPOSED SYSTEM MODEL

Considering an SC system with two transmit antennas and one receive antenna. The transmitter system model is shown in Fig. 1.

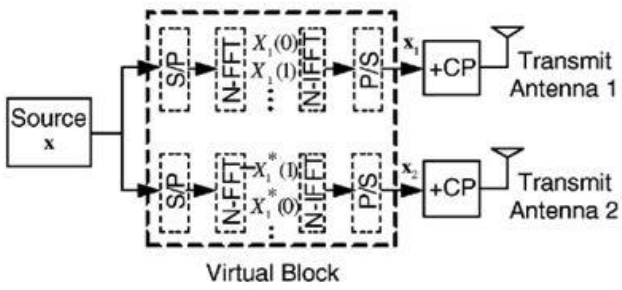

Fig. 1: The system model for transmitter.

Since, SFBC cannot be directly applied to an SC system, the equivalence of SFBC in the SC system is given by taking the transmit sequence from each transmit antenna as [12]

$$x_i(m) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X_i(k) W_N^{-mk} \tag{1}$$

where $m = 0,1,\ldots, N-1$ $i = 1, 2$, N is the length of FFT subcarriers, $X_i(k)$ is the k^{th} symbol to be transmitted from i^{th} antenna, $W_N = e^{-j2\pi/N}$ is the discrete Fourier transform(DFT) twiddle factor. The transmitted sequence from each transmit antenna can also be given as

$$x_i(m) = \frac{1}{\sqrt{2}}\left[x^e(m) + W_N^{-m} x^o(m)\right] \quad (2)$$

where $x^e(m) = \sqrt{\frac{2}{N}} \sum_{v=0}^{N/2-1} X_i(2v) W_{N/2}^{-vm}$ and $x^o(m) = \sqrt{\frac{2}{N}} \sum_{v=0}^{N/2-1} X_i(2v+1) W_{N/2}^{-vm}$ (3)

Applying the Alamouti scheme for transmit diversity as $X_1(v) = \begin{bmatrix} X_1(2v) \\ X_1(2v+1) \end{bmatrix}$ and $X_2(v) = \begin{bmatrix} -X^*_1(2v+1) \\ X_1(2v) \end{bmatrix}$ with $v = 0,1,\ldots, N/2-1$, the transmitted signals from each antenna is given as

$$x_1(m) = \frac{1}{\sqrt{2}}\left[x^e(m) + W_N^{-m} x^o(m)\right]$$
$$x_2(m) = \frac{1}{\sqrt{2}}\left[-x^{o*}(-m) + W_N^{-m} x^{e*}(-m)\right] \quad (4)$$

We assume the SC symbol transmission over an additive Gaussian noise frequency selective channel. Before transmission, a cyclic prefix of length N_p is added in front of the transmission sequence of each antenna, to eliminate the inter-block interference, and also makes the channel matrices circulant.

The receiver schematic is shown in Fig. 2.

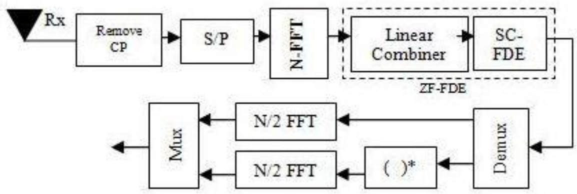

Fig. 2: Proposed receiver schematic

The received signal block of length N at the receiver after removing cyclic prefix is given as

$$\mathbf{r} = \mathbf{H}_1\mathbf{x}_1 + \mathbf{H}_2\mathbf{x}_2 + \mathbf{V} \quad (5)$$

where $\mathbf{H}_i$, $i = 1, 2$ is the i^{th} $N \times N$ circulant channel matrix, $\mathbf{x}_i = [x_i(0), x_i(1), \ldots, x_i(N-1)]^T$ is the transmitted block of length N from i^{th} antenna, $\mathbf{V}$ is the additive white Gaussian noise vector of length N, and $(.)^T$ denotes transposition. The channel matrix $\mathbf{H_i}$ is right circulant with its first column as the channel impulse response, the eigen decomposition of $\mathbf{H_i}$ is given as

$$\mathbf{H}_i = \boldsymbol{\psi}\boldsymbol{\rho}_i\boldsymbol{\psi}^H \quad (6)$$

where $\boldsymbol{\psi}$ is the $N \times N$ twiddle or orthonormal DFT matrix, $\boldsymbol{\rho}_i$ is the $N \times N$ diagonal matrix with diagonal elements as the channel frequency response, and $(.)^H$ denotes Hermitian transposition. Computing the DFT of Eq. (5), results in

$$\mathbf{R} = \boldsymbol{\rho}_1\mathbf{X}_1 + \boldsymbol{\rho}_2\mathbf{X}_2 + \mathbf{V}' \quad (7)$$

with $\mathbf{X}_i = [X_i(0), X_i(0), \ldots, X_i(N-1)]^T$, $i = 1, 2$, and $\mathbf{V}'$ is the DFT of $\mathbf{V}$. Dividing Eq. (7) into two parts,

$$R(2m) = \rho_1(2m) X_1(2m) - \rho_2(2m) X_1^*(2m+1) + V'(2m)$$
$$R^*(2m+1) = \rho_1^*(2m+1) X_1^*(2m+1) + \rho_2^*(2m+1) X(2m) + V_1'^*(2m+1) \quad (8)$$

with $m = 0, 1, \ldots, \frac{N}{2}-1$. Simply the Eq. (7) can be written in matrix form as

$$\mathbf{R}'_n = \begin{bmatrix} R(n) \\ R(n+1) \end{bmatrix} = \begin{bmatrix} \rho_1(n) & -\rho_2(n) \\ \rho_2(n+1) & \rho_1(n+1) \end{bmatrix} \begin{bmatrix} X_1(n) \\ X_1(n+1) \end{bmatrix} + \begin{bmatrix} V'(n) \\ V'(n+1) \end{bmatrix} \quad (9)$$

$$n = 0, 1, \ldots, \frac{N}{2}-1.$$

The channel is considered to be fast fading mobile environment, the channel coefficients of adjacent subcarriers are considered not equal. Applying matched filter (MF) equalization to Eq. (9) to obtain the estimated symbols as

$$\mathbf{Y}'_n = \begin{bmatrix} \rho_1(n) & -\rho_2(n) \\ \rho_2(n+1) & \rho_1(n+1) \end{bmatrix}^H \mathbf{R}'_n$$
$$\mathbf{Y}'_n = \begin{bmatrix} K_n & \varepsilon \\ \varepsilon & K_{n+1} \end{bmatrix} \begin{bmatrix} X_1(n) \\ X_1(n+1) \end{bmatrix} + \begin{bmatrix} \rho_1(n) & -\rho_2(n) \\ \rho_2(n+1) & \rho_1(n+1) \end{bmatrix}^H \begin{bmatrix} V'(n) \\ V'(n+1) \end{bmatrix} \quad (10)$$

where $K_n = |\rho_1(n)|^2 + |\rho_2(n)|^2$, $K_{n+1} = |\rho_1(n+1)|^2 + |\rho_2(n+1)|^2$ are the diversity gains, and $\varepsilon = \rho_2(n+1)\rho_1^*(n+1) - \rho_1^*(n)\rho_2(n+1)$ is the interference term.

In order to perfectly estimate the received symbols, eliminate the interference term produced by the MF receiver and to provide the full diversity gains as in classical ZF receiver, we propose a low complexity ZF equalizer matrix given as

$$\boldsymbol{\rho}_n^{LZF} = \begin{bmatrix} \rho_1(n) & \frac{\rho_2(n+1)}{G_n} \\ \rho_2^*(n) & \frac{\rho_1(n+1)}{G_n^*} \end{bmatrix} \quad (10)$$

where $G_n = \frac{\rho_2(n+1)}{\rho_2(n)} \frac{\rho_1^*(n+1)}{\rho_1^*(n)}$. Using the matrix defined in Eq. (10), the estimated symbol matrix is given as

$$\mathbf{Y}'_n = \boldsymbol{\rho}_n^{LZF}\mathbf{R}'_n$$
$$\mathbf{Y}'_n = \begin{bmatrix} K'_n & 0 \\ 0 & K'_{n+1} \end{bmatrix} \begin{bmatrix} X_1(n) \\ X_1(n+1) \end{bmatrix} + \boldsymbol{\rho}_n^{LZF} \begin{bmatrix} V'(n) \\ V'(n+1) \end{bmatrix} \quad (11)$$

where $K'_n = |\rho_1(n)|^2 + \frac{|\rho_2(n)|^2}{G_n}$, $K'_{n+1} = |\rho_1(n+1)|^2 + \frac{|\rho_2(n+1)|^2}{G_n^*}$ are the diversity gains of the low complexity ZF equalizer.

The final symbol detection in SC-FDE is made in the time-domain, and therefore, the estimated symbols must be transformed to time-domain by taking the $N/2$ point DFT of the estimated symbol, given in Eq. (11). The proposed low complexity ZF receiver results in zero interference term from the adjacent subcarriers in the estimated symbols. This method also avoids the inversion of channel matrix, as in classical ZF, which makes it lesser computationally complex than classical ZF for SC-FDE.

III. SIMULATION RESULTS

The performance of bit-error rate for two transmit antenna and one received antenna (SFBC SC-FDE) system was investigated through computer simulation. Considering a fast fading Rayleigh channel modelled using Jakes' model with fade rate, $f_D T_S$ □ 0.01 with QPSK modulation for the symbols to be transmitted, and block duration of N □ 64 symbols is taken to be 3.69 seconds as proposed in the third generation TDMA cellular standard EDGE [13]. The bit error rate (BER) performance, averaged over 100 iterations, was computed for proposed ZF SFBC SC-FDE system, and the results were compared with the classical ZF receiver. It is demonstrated in Fig. 3, that the proposed low complexity ZF receiver is equivalent to classical ZF for SC-FDE at each signal to noise ratio.

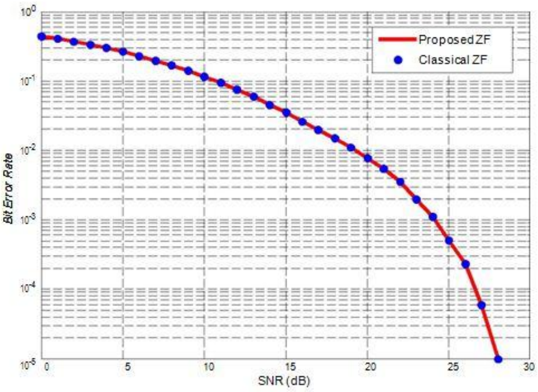

Fig. 3: BER of SFBC SC ZF-FDE for time varying Rayleigh fading channel with QPSK modulation and N = 64.

IV. CONCLUDING REMARKS

The proposed low complexity ZF equalizer is better than the classical ZF receiver and MF receiver for fast fading mobile environments for SC-FDE systems. The proposed system takes into account the advantages offered by SFBC and SC-FDE, and combines them into much lesser computationally complex ZF receiver. It has been shown that the proposed ZF receiver outperforms the MF receiver and matches with the classical ZF receiver, with the added advantage of lesser computations at the receiver for symbol estimation and detection.

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