STBC SC-FDE based on LS-Algorithm for Fixed Broadband Wireless Access System

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Abstract: We propose an Alamouti-like scheme for combining space-time block coding with single-carrier frequency-domain equalization(SC-FDE) in fixed broadband wireless access environment. With two transmit antennas, the scheme is shown to achieve significant diversity gains at low complexity over frequency-selective fading channels

Key words: – space-time block code(STBC), frequency-domain equalization (FDE), least squares

1. INTRODUCTION

With the tremendous growth of wireless systems including internet, demands for broadband wireless access technologies, offering bit rates of tens of megabits per second or more to residential and business subscribers, are increasing. Broadband wireless access technologies are attractive and economical alternatives to broadband wired access technologies. Broadband wireless access systems deployed in residential and business environments are likely to face hostile radio propagation environments, with multipath delay spread extending over tens of hundreds of bit intervals[1],[2].

For such broadband wireless metropolitan area network systems in licensed and unlicensed bands from 10 to 66 GHz are being developed by the IEEE 802.16 working group. Such systems, installed with minimal labor costs, may operate over non-line-of-sight links, serving residential and small office/home office subscribers. In such environments multipath can be severe. This raises the question of what types of anti-multipath measures are necessary, and consistent with low-cost solutions. Recently, there have been a number of proposals to anti-multipath. Among them, SC-FDE offers several advantages such as low complexity receivers (due to the use of the FFT), and reduced sensitivity to carrier frequency offset and nonlinear distortion in comparison to OFDM[1],[2],[3].

When combined with space-time block codes and the Alamouti scheme, SC-FDE can help increase system capacity without requiring additional bandwidth[4]. However, when implemented over frequency-selective channels, the Alamouti scheme should be implemented at a block and not symbol level in order to achieve multipath diversity gains. A low complexity STBC SC-FDE that achieves this goal was described by Al-Dhahir. But no previous works using least square estimation in fixed broadband wireless access(FBWA) environments have been reported.

In this paper, SC-FDE using least squares estimation of equalizer coefficients for STBC transmissions over FBWA channels is proposed. The outline of this paper is as follows. We start in section 2 by describing the SC-FDE using training sequence and LS(lease squares) algorithm. In section 3, we propose an Alamouti-like scheme for combining STBC and SC MMSE-FDE. Simulation results for the FBWA environment are given in section 4 and the paper is concluded in section 5

2. SC-MMSE FDE

2.1 Channel Model and Assumptions

We consider single-carrier block transmission over an additive-noise frequency-selective channel with memory ν. Each block of length N is appended with a length-ν *cyclic prefix*(CP) to eliminate interblock interference(IBI). A CP is formed by reproducing the sequence of the last ν transmitted symbols in a block, and adding this sequence to the beginning of the block before transmissions. At the receiver, the received CP is discarded before processing the block. Hence, out of every ($N+\nu$) received symbols, only N symbols are processed.

The input-output relationship can be expressed in matrix form as follows

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{n} \quad (1)$$

where $\mathbf{y}, \mathbf{x}$, and $\mathbf{n}$ are length-N blocks of received, input, and noise symbols. The input and noise symbols are assumed complex, zero-mean, and uncorrelated with variances σ_x^2 and σ_n^2, respectively. The $N \times N$ channel matrix $\mathbf{H}$ is *circulant* with first column equal to the channel impulse response (CIR) appended by ($N-\nu-1$) zeros
Since **H** is a circulant matrix, it has the eiven decomposition[4],[5].

$$\mathbf{H} = \mathbf{Q}^H \Lambda \mathbf{Q} \quad (2)$$

where $(\cdot)^H$ denotes complex-conjugate transpose; $\mathbf{Q}$ is the orthonormal discrete Fourier transform(DFT) matrix whose (l,k) element is given by $\mathbf{Q}(l,k) = 1/\sqrt{N}e^{-j2\pi/Nlk}$ where $0 \le l,k \le N-1$; and

Λ is a diagonal matrix whose (k,k) entry is equal to the kth DFT coefficient of the CIR

2.2 SC-MMSE FDE using Perfect Channel

Fig 1. illustrates a SC-FDE with linear equalization. After discarding the cyclic prefix, the received time-domain block $\mathbf{y}$ is transformed to the frequency domain by applying the DFT[4].

$$\begin{aligned}\mathbf{Y} &= \mathbf{Qy} = \mathbf{\Lambda Qx} + \mathbf{Qn} \\ &= \mathbf{\Lambda X} + \mathbf{N}\end{aligned} \tag{3}$$

The SC-MMSE FDE is represented by the $N \times N$ diagonal matrix $\mathbf{W}$ whose (i,i) element is given by

$$W(i,i) = \frac{\Lambda^H(i,i)}{\left|\Lambda^H(i,i)\right|^2 + \frac{1}{SNR}} \tag{4}$$

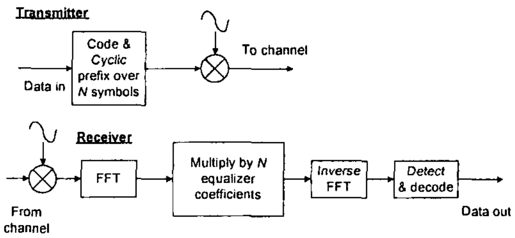

Fig. 1. SC-FDE with Linear Equaliziation

where $SNR = \frac{\sigma_x^2}{\sigma_n^2}$.

The SC MMSE-FDE output, denoted by $\mathbf{Z} = \mathbf{WY}$, is transformed back to time-domain resulting in length- N vector $\mathbf{z}$ given by

$$\mathbf{z} = \mathbf{Q}^H\mathbf{Z} = \mathbf{Q}^H\Lambda^H(\Lambda\Lambda^H + \frac{1}{SNR}\mathbf{I}_N)^{-1}\Lambda\mathbf{Qx} + \tilde{\mathbf{n}} \tag{5}$$

where $\tilde{\mathbf{n}} = \mathbf{Q}^H\mathbf{WQn}$. Finally, hard decisions are made on $\mathbf{x}$ by applying $\mathbf{z}$ to a slicer.

2.3 SC-MMSE FDE using Channel Estimation

2.3.1 Cyclic Prefix versus Unique Word

Generally, equalization and decoding of SC-FDE require channel state information(CSI) at the receiver, which can be estimated using training sequences embedded in each block. Here, CP is less useful for other purposes like channel estimation, equalization, or synchronization as long as the content of the CP is not known and varies with every single block. The overhead induced by the CP could be used in a more efficient way if its content would be known before and could be chosen in a proper way.

We will now given a mathematical description of the investigated SC/FDE system when using unique word(UW) instead of the traditional CP. Ideally its frequency spectrum should have equal or nearly equal magnitude for all frequencies. Such an ideal training sequence ensures that each frequency component of the channel is probed uniformly. For unique word lengths that are powers of two, such as 64 or 256, poly phase Frank-Zadoff sequences or Chu sequences are suitable[2].

Fig. 2 depicts the structure of transmitted block, which consists of the original data sequence of N_s symbols and the sequence of the UW with N_G symbols. The overall duration of $N = N_S + N_G$ symbols is $T_{FFT} = NT$

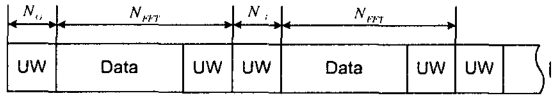

Fig. 2. Transmitted block using the concept of UW

But the bundwidth efficiency is reduced for a SC/FDE by the roll-off factor r on the one hand and by the guard period on the other hand. A simple estimation of the bandwidth efficiency of the described SC/FDE-CP system without taking coding into account can be given as:

$$\begin{aligned}\eta_{CP} &= \frac{M}{1+r}\left(\frac{N_{FFT}}{N_{FFT}+N_G}\right)\left[\frac{bit/s}{Hz}\right] \\ \eta_{UW} &= \frac{M}{1+r}\left(\frac{N_{FFT}-N_G}{N_{FFT}}\right)\left[\frac{bit/s}{Hz}\right]\end{aligned} \tag{6}$$

M describes the number of bits per symbol. This leads to an additional degradation of 4% in terms of bandwidth efficiency, assuming T_G to be 20% of T_{FFT}. For channel estimation, at least two adjacent UW blocks are necessary

2.3.2 Channel Estimation using Unique Word

We consider the estimation of the equalizer parameters $\mathbf{W}$ from the reception of N consecutive training blocks, each consisting of a sequence of P known transmitted training symbols $\{a_k, k = 0,1,\cdots,P-1\}$. Estimation of the equalizer parameters is based on LS optimization. Estimated channel coefficients $\tilde{\Lambda}$ and denominator of equation (4) is;

$$\tilde{\Lambda} = \frac{1}{N}\sum_{n=1}^{N}\frac{\mathbf{Y}}{\mathbf{A}} \tag{7}$$

$$\tilde{\mathbf{U}} = \frac{1}{N}\sum_{n=1}^{N}\left|\frac{\mathbf{Y}}{\mathbf{A}}\right|^2 \tag{8}$$

Therefore, estimated equalizaer coefficients

$$\tilde{\mathbf{W}} = (\tilde{\mathbf{U}})^{-1}\tilde{\mathbf{H}}^* \tag{9}$$

Interpolation from P forward equalizer coefficients to M coefficients is done in the frequency domain: the inverse FFT, of length P, of each component of the vector $\mathbf{Y}/\mathbf{A}$ is computed, the resulting sequences are padded with zeroes to length M, and the FFT is taken; the resulting version of $\mathbf{Y}/\mathbf{A}$ is of length M, and is used to compute $\tilde{\Lambda}$ and $\tilde{\mathbf{U}}$

3. STBC SC-MMSE FDE

3.1 SC-MMSE FDE for STBC Transmission

Denote the nth symbol of the kth transmitted block from antenna i by $\mathbf{x}_i^{(k)}(n)$. At times k=0,2,4,..., pairs of length-N blocks $\mathbf{x}_1^{(k)}(n)$ and $\mathbf{x}_2^{(k)}(n)$ (for $0 \le n \le N-1$) are generated by an information source. Inspired by the Alamouti STBC, we propose the following transmit diversity scheme. Fig. 3 shows the block format for proposed transmission scheme

$$\begin{aligned} \mathbf{x}_1^{(k+1)}(n) &= -\mathbf{x}_2^{*(k)}((-n)_N) \\ \mathbf{x}_2^{(k+1)}(n) &= \mathbf{x}_1^{*(k)}((-n)_N) \\ &, n = 0,1,\ldots,N-1, \quad k = 0,2,4,\ldots \end{aligned} \qquad (10)$$

where $(\bar{\cdot})$ and $(\cdot)_N$ denote complex conjugation and modulo-N operations, respectively.

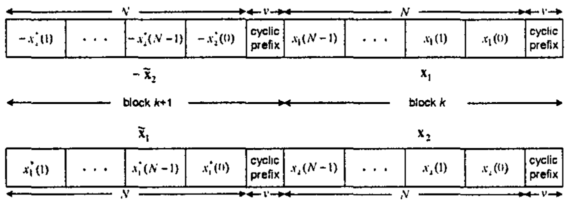

Fig. 3. Block format for proposed transmission

In addition, a CP of length ν is added to each transmitted block to eliminate IBI and make al channel matrices circulant. Finally, the transmitted power from each antenna is half its value in the single-transmit case so that total transmitted power is fixed[4].

With two transmit and two receive antenna, received blocks k and $k+1$ are given by

$$\mathbf{y}_i^{(j)} = \mathbf{H}_{1i}^{(j)}\mathbf{x}_1^{(j)} + \mathbf{H}_{2i}^{(j)}\mathbf{x}_2^{(j)} + \mathbf{n}_i^{(j)}, j = k, k+1, i = 1,2 \quad (10)$$

where $\mathbf{H}_{1i}^{(j)}, \mathbf{H}_{2i}^{(j)}$ are the circulant channel matrices from transmit antennas 1 and 2, respectively, over block j, to the receive antenna. Analogous to the single-transmit case, by applying the DFT to $\mathbf{y}^{(j)}$, we get

$$\begin{aligned} \mathbf{Y}_i^{(j)} &= \mathbf{Q}\mathbf{y}_i^{(j)} \\ &= \mathbf{\Lambda}_{1i}^{(j)}\mathbf{X}_1^{(j)} + \mathbf{\Lambda}_{2i}^{(j)}\mathbf{X}_2^{(j)} + \mathbf{N}_i^{(j)} \quad, i = 1,2 \end{aligned} \qquad (11)$$

where $\mathbf{X}_i = \mathbf{Q}\mathbf{x}_i, \mathbf{N}_i^{(j)} = \mathbf{Q}\mathbf{n}^{(j)}$. Using the encoding rule in (10) and properties of the DFE, we have

$$\begin{aligned} \mathbf{X}_1^{(k+1)}(m) &= -\overline{\mathbf{X}}_2^{(k)}(m) \\ \mathbf{X}_2^{(k+1)}(m) &= \overline{\mathbf{X}}_1^{(k)}(m), m = 0,1,\ldots,N-1, k = 0,2,4,\ldots \end{aligned} \qquad (12)$$

. Furthermore, we assume that channels are fixed over two consecutive blocks, i.e.,

$$\begin{aligned} \mathbf{H}_{1i}^{(k+1)} = \mathbf{H}_{1i}^{(k)} = \mathbf{H}_{1i} \\ \mathbf{H}_{2i}^{(k+1)} = \mathbf{H}_{2i}^{(k)} = \mathbf{H}_{2i} \end{aligned} \Leftrightarrow \begin{aligned} \mathbf{\Lambda}_{1i}^{(k+1)} = \mathbf{\Lambda}_{1i}^{(k)} = \mathbf{\Lambda}_{1i} \\ \mathbf{\Lambda}_{2i}^{(k+1)} = \mathbf{\Lambda}_{2i}^{(k+1)} = \mathbf{\Lambda}_{2i} \end{aligned} \qquad (13)$$

Combining (7)-(9), we get

$$\begin{aligned} \mathbf{Y} = \begin{bmatrix} \mathbf{Y}_1 \\ \mathbf{Y}_2 \end{bmatrix} = \begin{bmatrix} \mathbf{Y}_1^{(k)} \\ \overline{\mathbf{Y}}_1^{(k+1)} \\ \mathbf{Y}_2^{(k)} \\ \overline{\mathbf{Y}}_2^{(k+1)} \end{bmatrix} &= \begin{bmatrix} \mathbf{\Lambda}_{11} & \mathbf{\Lambda}_{21} \\ \mathbf{\Lambda}_{21}^H & -\mathbf{\Lambda}_{11}^H \\ \mathbf{\Lambda}_{12} & \mathbf{\Lambda}_{22} \\ \mathbf{\Lambda}_{22}^H & -\mathbf{\Lambda}_{12}^H \end{bmatrix} \begin{bmatrix} \mathbf{X}_1^{(k)} \\ \mathbf{X}_2^{(k)} \end{bmatrix} + \begin{bmatrix} \mathbf{N}_1^{(k)} \\ \overline{\mathbf{N}}_2^{(k+1)} \end{bmatrix} \\ &= \mathbf{\Lambda}\mathbf{X} + \mathbf{N} \end{aligned}$$
(14)

Since $\mathbf{\Lambda}$ is an orthogonal matrix, we can (without loss of optimality) multiply both sides of (14) by $\mathbf{\Lambda}^*$ to decouple the two signals $\mathbf{X}_1^{(k)}$ and $\mathbf{X}_2^{(k)}$ resulting in

$$\widetilde{\mathbf{Y}} = \mathbf{\Lambda}^H\mathbf{Y} = \begin{bmatrix} \widetilde{\mathbf{\Lambda}} & \mathbf{0} \\ \mathbf{0} & \widetilde{\mathbf{\Lambda}} \end{bmatrix} \begin{bmatrix} \mathbf{X}_1^{(k)} \\ \mathbf{X}_2^{(k)} \end{bmatrix} + \widetilde{\mathbf{N}} \qquad (15)$$

where $\widetilde{\Lambda}$ is an $N \times N$ diagonal matrix

$$\widetilde{\mathbf{\Lambda}} = \sum_{j=1}^{2}\sum_{i=1}^{2}\left|\mathbf{\Lambda}_{ij}\right|^2 = \sum_{j=1}^{2}\sum_{i=1}^{2}\left|\mathbf{\Lambda}_{ij}(m,m)\right|^2 \qquad (16)$$

Above procedure shown in Fig. 4

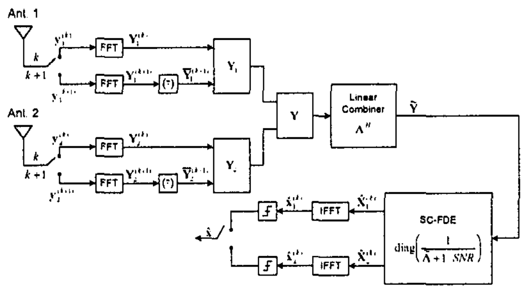

Fig. 4. Frequency domain combining and MMSE FDE

3.2 STBC SC-FDE using Channel Estimation

We consider the estimation of the equalizer parameters $\mathbf{W}$ from the reception of N consecutive training blocks, each consisting of a sequence of P known transmitted training symbols $\{a_k, k = 0,1,\cdots,P-1\}$.

First, received signal of lth training block of ith antenna is

$$\begin{aligned} \mathbf{Z}_{il} = \begin{bmatrix} \mathbf{Z}_{il}^{(k)} \\ \mathbf{Z}_{il}^{(k+1)} \end{bmatrix} &= \begin{bmatrix} \mathbf{U}_1 & \mathbf{U}_2 \\ -\mathbf{U}_2^H & \mathbf{U}_1^H \end{bmatrix} \begin{bmatrix} \mathbf{\Gamma}_{1il} \\ \mathbf{\Gamma}_{2il} \end{bmatrix} + \begin{bmatrix} \mathbf{N}_{il}^1 \\ \mathbf{N}_{il}^2 \end{bmatrix} \\ &= \mathbf{U}\mathbf{\Gamma}_i + \mathbf{N}_{il} \end{aligned} \qquad (17)$$

where $\mathbf{U}_1$ and $\mathbf{U}_2$ are training sequence and Γ_{1il} and Γ_{2il} are estimated channels in lth block.

Multiply both sides of (17) by $\mathbf{\Lambda}^H$ to channel estimation.

$$\widetilde{\mathbf{Z}}_{il} = \begin{bmatrix} \widetilde{\mathbf{Z}}_{il}^{(k)} \\ \widetilde{\mathbf{Z}}_{il}^{(k+1)} \end{bmatrix} = \mathbf{U}^*\mathbf{Z}_{il} = \begin{bmatrix} \widetilde{\mathbf{U}} & \mathbf{0} \\ \mathbf{0} & \widetilde{\mathbf{U}} \end{bmatrix} \begin{bmatrix} \mathbf{\Gamma}_{1il} \\ \mathbf{\Gamma}_{2il} \end{bmatrix} + \widetilde{\mathbf{N}}_{il} \quad (18)$$

where $\widetilde{\mathbf{U}} = \left|\widetilde{\mathbf{U}}_1\right|^2 + \left|\widetilde{\mathbf{U}}_2\right|^2$.

Therefore estimated channel coefficients is

$$\tilde{\Gamma}_{il} = \begin{bmatrix} \tilde{\Gamma}_{1il} \\ \tilde{\Gamma}_{2il} \end{bmatrix} = \begin{bmatrix} \tilde{U}^{-1} & 0 \\ 0 & \tilde{U}^{-1} \end{bmatrix} \begin{bmatrix} \tilde{Z}_{il}^{(k)} \\ \tilde{Z}_{il}^{(k+1)} \end{bmatrix} \quad (19)$$

Estimated channel coefficients are obtained from *L*-block training sequence. In equation (15) , the matrix $\tilde{\Lambda}$ can be approximated by diagonal version of $\tilde{\Gamma}_{il}$

4. SIMULATION RESULTS

The symbol error rate performance of SC-FDE, using perfect channel knowledge, and with training, has been evaluated by simulation using several models of FBWA channels with multipath fading. Fig. 4 depicts the delay spread profile for channel 'SUI-5', one of six channel models adopted by IEEE 802.16.3 for evaluating broadband wireless system in 2-11 GHz bands

SUI-5 channel is a high delay spread model associated with the use of omnidirectional antennas in suburban hilly environments. The channel has a maximum delay spread of $10\mu s$, and a rms delay spread of $3.05\mu s$. Each of the three echoes at 0, 5, 10 μs is modeled as an independent complex Gaussian random variable, with relative variances of 0, -5 and -10 dB respectively. The fading was modeled as quasi-static. Bandwidth is 5MHz and the Length of CP is 64. QPSK, 14QAM, 64QAM SC-FDE systems were simulated against this model for range of received signal to noise ratio.

Fig. 5. and Fig. 6 show that SER curves with perfect channel knowledge. From this figure, significant improvement achieved in SC MMSE-FDE performance when combining it with the STBC scheme. Fig. 7. shows that performance comparison according to antenna scheme in case of LS algorithm.

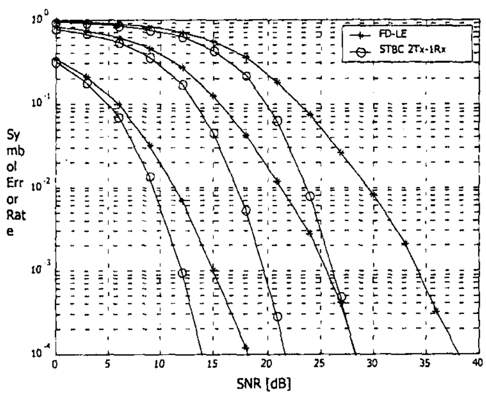

Fig. 5. Performance comparison for systems with prefect channel knowledge

5. CONCLUSIONS

We presented a low-complexity SC transmit-diversity scheme for frequency-selective channels. This scheme combines the advantages of an Alamouti-like space time block coding scheme and FFT-based SC-FDE using LS algorithm. Significant performance gains over single-antenna transmission were demonstrated for the FBWA channels

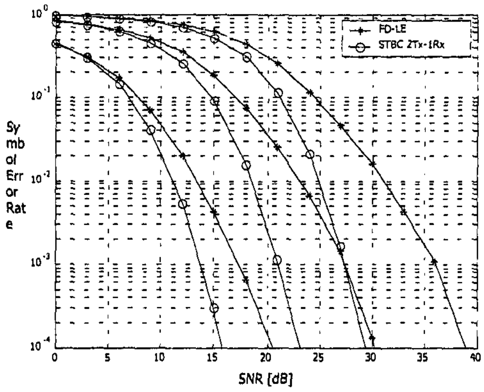

Fig. 6. Performance comparison for systems with LS algorithm

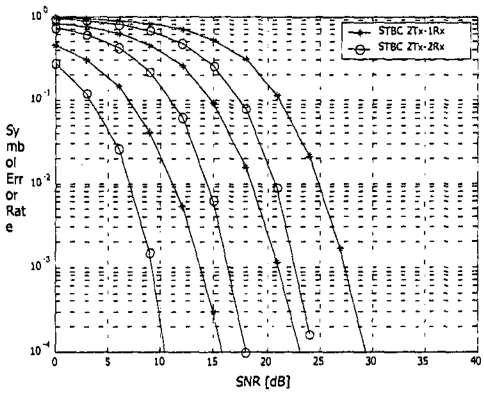

Fig. 7. Performance comparison for systems according to antenna scheme

References

[1] D. Falconer et. al., "Frequency domain equalization for single-carrier broadband wireless systems," IEEE Commun. Mag., vol. 40, no. 4, pp. 58–66, Apr. 2002.

[2] N. Al-Dhahir, "Single-carrier frequency-domain equalization for space-time block-coded transmissions over frequency-selective fading channels," IEEE Commun. Lett., vol. 16, no. 8, pp. 1451–1458, Oct. 1998.

[3] S. L. Ariyavisitakul, A. B. B. Eidison. B. Falconer, "Frequency domain equalization for single-carrier broadband wireless systems," [Online]. Available: www.sce.carleton.ca/bbw/papers/Ariyavisitakul.pdf

[4] S. M. Alamouti, "A simple transmit diversity technique for wireless communications," IEEE J. Select. Area Commun., vol. 16. pp. 1451–1458, Oct. 1998.

[5] V. Tarokh et. al., "Space-time block codes from orthogonal designs," IEEE Trans. Inform. Theory, vol. 45, pp. 1456–1467, July 1999.