A JOINT CODED TWO-STEP MULTIUSER DETECTION SCHEME FOR MIMO OFDM SYSTEM

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ABSTRACT

Multiple-input, multiple-output (MIMO) communication is an effective scheme to improve wireless communication performance of multiuser applications. However, reliable communication in multiuser systems is affected by the presence of both multi-access interference (MAI) and inter-symbol interference (ISI) in multi-path channels. In this paper, we therefore investigate a transceiver design for a wideband multiuser-MIMO communication system, where the co-channel users are equipped with multiple transmit and multiple receive antennas. In particular, we propose a two-step interference cancellation scheme with an error correction coding technique for the receiver of a multiuser uplink system. The scheme employs orthogonal frequency division multiplexing (OFDM) modulation and space-time block codes (STBC). The receiver performs as a soft output multiuser detector based on minimum mean-squared error (MMSE) interference suppression at the first stage, and then, MAI cancellation is implemented with a bank of single-user channel decoders. The paper also includes computer simulations which help to improve the understanding of specific issues involved in the design of multiuser STBC-OFDM systems, and confirm the utility of the proposed approach.

Index Terms— Multiuser detection, MIMO-OFDM, MAI, interference cancellation, error control coding.

1. INTRODUCTION

Nowadays, wireless communications can provide high data rate and high quality information transmission. However, the demand for multimedia services with high data rates in a multiuser communication platform is a major challenge of the current industry. A significant amount of research has addressed various multiuser methods for interference suppression e.g.[1]. In particular, spectrally efficient techniques such as OFDM, coding techniques, MIMO and co-channel multiuser communications are key physical layer research targets. The introduction of MIMO techniques in the late 1990s has renewed the interest in multi-path channel capacity: that is, for a system with n transmit antennas and m receive antennas the capacity can be increased linearly with $\min(n, m)$ without increasing the power or the bandwidth. Although MIMO point-to-point communication has attracted considerable research interest during the last decade, only recently has multiuser MIMO received attention. On the other hand, OFDM is a very popular and robust technique that can mitigate the effect of ISI resulting from the presence of delay spread in a MIMO application, whereby frequency selective fading channels are transformed into multiple flat fading sub channels with the help of a cyclic prefix, and can be effectively combined with space-time block codes originally designed for flat fading channels. In practice, OFDM may be used in combination with space-time block codes.

However, the performance of such STBC-OFDM systems may seriously degrade in the presence of multiple-access interference (MAI) resulting from multiuser communications when multiple users are allowed to access the same channel simultaneously. Therefore, it is of importance to design a system receiver that can suppress co-channel interference by including a suitable multiuser detection scheme and effective channel equalizer.

In this paper, a joint interference cancellation scheme is considered for a wide-band uplink system with K synchronous co-channel users, each is equipped with space-time block coded (STBC) and OFDM modulated transmit antennas (see [2] and [3]). In OFDM modulation, assuming that the frequency response of the channel remains constant over two consecutive blocks, we propose to employ STBC over two adjacent time-domain blocks. The number of transmit antennas per user is limited to $n_t = 2$. The receiving station is equipped with m $(\geq K)$ receive antennas. The challenge is to design a receiver that can suppress the co-channel interferences and inter-symbol interferences simultaneously. We therefore extend the narrow band uncoded interference suppression and cancellation scheme proposed in [3] to the proposed wideband channels and also incorporate error correction coding.

Notation: Bold upper case $\mathbf{X}$ denotes a matrix and lowercase $\mathbf{x}$ denotes a vector. $\mathbf{X}^{(i)}$ and $\mathbf{x}^{(i)}$ denote the signal matrix and vector corresponding to the ith user. We use $x(k)$ to denote the kth element of the vector $\mathbf{x}$ of size N, where $k = 0, 1, \ldots N-1$. $\mathbf{x}_n$ denotes the nth block vector in the data stream. The matrix indexed by q and j is denoted by $\mathbf{X}_{qj}$. $\mathbf{I}_N$ is an identity matrix of size N. Complex conjugation, transposition and conjugate transposition of a matrix are respectively denoted by $(\cdot)^*$, $(\cdot)^T$ and $(\cdot)^H$.

2. SYSTEM MODEL

We consider a K-user space-time block coded OFDM wireless communication system, where each user terminal is equipped with $n_t = 2$ transmit antennas. First, the incoming data stream is encoded by a half rate convolutional encoder and mapped as QPSK. Then, space-time block encoding processing is implemented on the signal and the OFDM modulator is applied to the outputs of the space time encoder.

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The outputs of the OFDM modulators are transmitted using multiple antennas simultaneously.

Here, we examine space-time block codes combined with OFDM modulation. In this scheme, the temporal index in each block corresponds to the tone index of OFDM. This requires that the channel remains constant over a number, two in this work, of consecutive blocks equal to the number of transmit antennas n_t (see in [4]). The ith user's input, $i = 1,\ldots,K$, is two consecutive blocks, denoted as $s_1^{(i)}$ and $s_2^{(i)}$. Each block is then channel encoded, interleaved and symbol mapped to form the two OFDM blocks of length N, denoted as $\mathbf{x}_1^{(i)} = [x_1^{(i)}(0),\cdots,x_1^{(i)}(N-1)]^T$ and $\mathbf{x}_2^{(i)} = [x_2^{(i)}(0),\cdots,x_2^{(i)}(N-1)]^T$ in the frequency domain. In this paper, we describe the transmission in terms of the frequency domain, as the method is extended from [4] and [6], and because we consider the transmission over frequency-selective fading channels; hence, the equivalent frequency channel response is represented in a diagonal matrix form as $diag[H_{qj}^i(0),H_{qj}^i(1),\ldots,H_{qj}^i(N-1)]$ (see in [6] and [8]). Here, $H_{1j}^i(k)$ and $H_{2j}^i(k)$ denote the channel frequency responses of the kth tone, related to the channel from the $1st$ and $2nd$ transmit antennas and corresponding to the ith user and the jth receive antennas, respectively, over two contiguous signal block intervals. Due to employing a space-time block encoding scheme, the kth tone receive symbol is in the frequency domain over the two sequential OFDM time-slots 1 and 2, respectively,

$$r_{1j}(k) = \sum_{i=1}^{K}\{H_{1j}^i(k)x_1^{(i)}(k) + H_{2j}^i(k)x_2^{(i)}(k)\} + v_{1j}(k) \tag{1}$$

$$r_{2j}(k) = \sum_{i=1}^{K}\{H_{2j}^i(k)x_1^{(i)*}(k) - H_{1j}^i(k)x_2^{(i)*}(k)\} + v_{2j}(k) \tag{2}$$

where $k = 0,1,\ldots,N-1$ and $[v_{1j}(k)\ v_{2j}(k)]$ denote the frequency domain representation of the receiver AWGN at the kth tone. We next define $\mathbf{r}_j(k) = [r_{1j}(k)\ r_{2j}^*(k)]^T$, $\mathbf{x}^{(i)}(k) = [x_1^{(i)}(k)\ x_2^{(i)}(k)]^T$, $\mathbf{v}_j(k) = [v_{1j}(k)\ v_{2j}^*(k)]^T$ and $\breve{\mathbf{H}}_j^i = \begin{bmatrix} H_{1j}^i(k) & H_{2j}^i(k) \\ H_{2j}^{i\ *}(k) & -H_{1j}^{i\ *}(k) \end{bmatrix}$, where $\breve{\mathbf{H}}_j^i$ is the equivalent channel response matrix of the kth tone between the ith user terminal and the jth receive antenna. The kth tone receive signals from all receive antennas during two consecutive OFDM periods can be represented in matrix form as follows:

$$\begin{bmatrix} \mathbf{r}_1(k) \\ \mathbf{r}_2(k) \\ \vdots \\ \mathbf{r}_m(k) \end{bmatrix} = \begin{bmatrix} \breve{\mathbf{H}}_1^1(k) & \cdots & \breve{\mathbf{H}}_1^K(k) \\ \breve{\mathbf{H}}_2^1(k) & \cdots & \breve{\mathbf{H}}_2^K(k) \\ \vdots & \ddots & \vdots \\ \breve{\mathbf{H}}_m^1(k) & \cdots & \breve{\mathbf{H}}_m^K(k) \end{bmatrix} \begin{bmatrix} \mathbf{x}^{(1)}(k) \\ \mathbf{x}^{(2)}(k) \\ \vdots \\ \mathbf{x}^{(K)}(k) \end{bmatrix} + \begin{bmatrix} \mathbf{v}_1(k) \\ \mathbf{v}_2(k) \\ \vdots \\ \mathbf{v}_m(k) \end{bmatrix} \tag{3}$$

We re-write the received signal for simplicity of notation as follows:

$$\tilde{\mathbf{r}}(k) = \tilde{\mathbf{H}}(k)\tilde{\mathbf{x}}(k) + \mathbf{v}(k) \tag{4}$$

where $\tilde{\mathbf{r}}(k)$ is the overall receive signal vector at all receive antennas with $2m$ elements, $\tilde{\mathbf{H}}(k)$ is the equivalent overall channel response matrix of size $2m \times 2K$, $\tilde{\mathbf{x}}(k)$ is the transmitting signal vector with $2K$ elements including all users at the kth tone, and $\mathbf{v}(k)$ is the equivalent complex noise vector of size $2m$ which influences the overall channels.

3. JOINT CODED TWO STEP INTERFERENCE CANCELLATION

We extend the two-step generalized MMSE interference receiver in [3] to the proposed multiuser STBC-OFDM scheme. For simplicity, we consider the two-user scenario. The receiver structure is illustrated in Fig 1.

In this receiver structure, the OFDM-demodulated received signal will be passed through the following five parts of processing:
(1) Soft signal value estimation based on a combined MMSE and multiuser detector.
(2) Soft-input-hard-output (SIHO) Viterbi decoding to correct error.
(3) Multiple-access interference cancellation and symbol re-estimation using the modified interference-free received signal.
(4) Decision based on the reliability estimation.
(5) Channel decoding to obtain the final estimation signal.

3.1. Step 1: Linear MMSE Interference Suppression and Viterbi Decoding

We use MMSE interference cancellation and error correction by SIHO Viterbi decoding to estimate the transmitted symbols. Consider the ith user terminal, where $i = 1,2$. We define the following cost function to minimize the mean squared error caused by co-channel interference and noise in the symbol $\hat{x}^{(i)}$, where $\hat{x}^{(i)} = \mathbf{w}\tilde{\mathbf{r}}$ is the estimation of the symbol $x^{(i)}$: $J(\mathbf{w}) = E\left\{\left\|x^{(i)} - \mathbf{w}\tilde{\mathbf{r}}(k)\right\|^2\right\}$, where $E\{\cdot\}$ and $\|\cdot\|^2$ denote the statistical expectation operator and squared Euclidean norm operator, respectively. To minimize the mean squared error, we choose the weight vector $\mathbf{w}$ of size $2m$ based on standard minimization: $\frac{\partial J(\mathbf{w})}{\partial \mathbf{w}} = \mathbf{0}$. Hence, the weight vectors $\mathbf{w}_{2i-1} = [w_{2i-1,1}, w_{2i-1,2}, \ldots, w_{2i-1,2m}]$ and $\mathbf{w}_{2i} = [w_{2i,1}, w_{2i,2}, \ldots, w_{2i,2m}]$, corresponding to the ith user, can be computed respectively, as

$$\mathbf{w}_{2i-1} = \mathbf{M}^{-1}\tilde{\mathbf{h}}_{2i-1} \tag{5}$$

$$\mathbf{w}_{2i} = \mathbf{M}^{-1}\tilde{\mathbf{h}}_{2i} \tag{6}$$

where $\mathbf{M} = \tilde{\mathbf{H}}(k)\tilde{\mathbf{H}}^H(k) + \frac{1}{\tau}\mathbf{I}_{2m}$ and $\tau = E_s/N_0$ is the signal to noise ratio, $\tilde{\mathbf{h}}_{2i-1}$ and $\tilde{\mathbf{h}}_{2i}$ are the $(2i-1)$th and $(2i)$th columns of $\tilde{\mathbf{H}}(k)$, respectively. Hence, we can obtain the soft estimation symbols written as $\lambda_1^{(i)}(k) = \mathbf{w}_{2i-1}^*\tilde{\mathbf{r}}(k)$ and $\lambda_2^{(i)}(k) = \mathbf{w}_{2i}^*\tilde{\mathbf{r}}(k)$.

The $\lambda_1^{(i)}(k)$ and $\lambda_2^{(i)}(k)$ values are passed through the Viterbi decoder for advance error correction, and then we obtain scalar decision symbols $\hat{x}_1^{(i)}(k)$ and $\hat{x}_2^{(i)}(k)$, on which independent decisions can be formed

Finally, the error correction reliability value for the whole first step estimation of the ith user's symbol can be represented as

$$\triangle_{\hat{\mathbf{x}}^{(i)}(k)} = \left\|\lambda_1^{(i)}(k) - \hat{x}_1^{(i)}(k)\right\|^2 + \left\|\lambda_2^{(i)}(k) - \hat{x}_2^{(i)}(k)\right\|^2 \tag{7}$$

3.2. Step 2: Two-Step Approach for MAI Cancellation and Symbol Re-Estimation

In Step 1, a linear MMSE scheme and symbol error correction by SIHO Viterbi decoding is used to suppress the interferences from the co-channel users in estimating the transmitted information symbols. In the second step, we re-estimate the transmitted symbols based on a modified received signal obtained by cancelling the multiple access interferences. Note that a perfect interference cancellation may be achieved only if the signals from the first step have been decoded correctly. In the case of two users, in order to estimate the second user symbols, the receiver cancels the multiple access interference (MAI) caused by the first user from the received signals $\mathbf{r}_1(k), \mathbf{r}_2(k), \ldots, \mathbf{r}_m(k)$ to estimate the transmitted symbols. For the

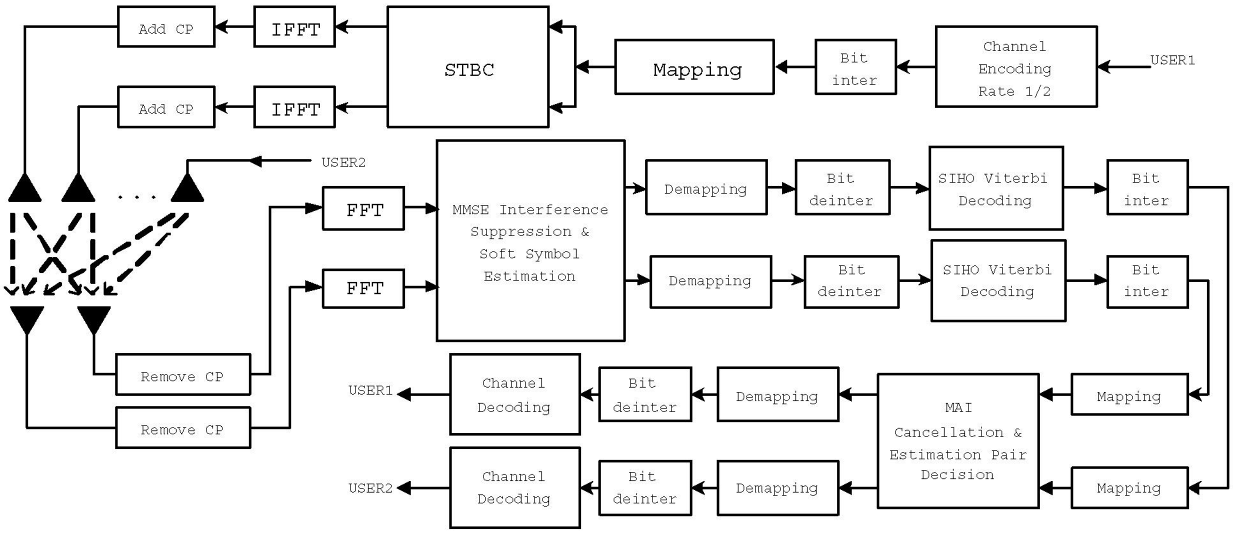

Fig. 1. Proposed two user joint STBC MIMO-OFDM wireless transmission system

kth tone, the modified received signal from the nth receive antenna after cancelling the MAI from the first user will be represented as

$$\mathbf{a}_n(k) = \mathbf{r}_n(k) - \breve{\mathbf{H}}_n^1(k)\hat{\mathbf{x}}^{(1)}(k) \quad (8)$$

The second user's kth signals are re-decoded using the above modified received vector:

$$\hat{\hat{\mathbf{x}}}^{(2)}(k) = \arg \min_{\hat{\hat{\mathbf{x}}}^{(2)} \in \mathbf{x}} \sum_{n=1}^{m} \left\{ \left\| \mathbf{a}_n - \breve{\mathbf{H}}_n^2(k)\hat{\hat{\mathbf{x}}}^{(2)}(k) \right\|^2 \right\} \quad (9)$$

where $\mathbf{x}$ includes all possible choices of QPSK symbols. The reliability function for the estimation from this second step of user 2 will be given by

$$\triangle_{\hat{\hat{\mathbf{x}}}^{(2)}(k)} = \sum_{n=1}^{m} \left\{ \left\| \mathbf{a}_n - \breve{\mathbf{H}}_n^2(k)\hat{\hat{\mathbf{x}}}^{(2)}(k) \right\|^2 \right\} \quad (10)$$

Finally, the total reliability of the first and second step estimation will be the summation of the reliability of the first user at the first step and the reliability of the second user at the second step, which is given by the overall reliability $\triangle_a = \triangle_{\hat{\mathbf{x}}^{(1)}(k)} + \triangle_{\hat{\hat{\mathbf{x}}}^{(2)}(k)}$ for $\hat{\mathbf{x}}^{(1)}(k)$ and $\hat{\hat{\mathbf{x}}}^{(2)}(k)$. This procedure will be repeated assuming a correct decision for the second user at the first step and based upon its estimate, the user 1 signals will be re-estimated.

At the next step, the receiver then repeats the MAI interference cancellation and symbol-wise likelihood re-estimation algorithm, assuming that the estimation of the second user transmitted signal at the kth tone $\hat{\mathbf{x}}^{(2)}(k) = [\hat{x}_1^{(2)}(k), \hat{x}_2^{(2)}(k)]^T$ has been decoded correctly at the first step. In a similar fashion, we can also define the reliability function as $\triangle_b = \triangle_{\hat{\mathbf{x}}^{(2)}(k)} + \triangle_{\hat{\hat{\mathbf{x}}}^{(1)}(k)}$ to denote the overall reliability for $\hat{\mathbf{x}}^{(2)}(k)$ and $\hat{\hat{\mathbf{x}}}^{(1)}(k)$.

Then, the symbol pairs based on the best overall reliabilities obtained between Δ_a and Δ_b will be the focus. When $\triangle_a < \triangle_b$, the pair $[\hat{\mathbf{x}}^{(1)}(k), \hat{\hat{\mathbf{x}}}^{(2)}(k)]$ will be chosen as the estimates, otherwise, it will be $[\hat{\hat{\mathbf{x}}}^{(1)}(k), \hat{\mathbf{x}}^{(2)}(k)]$.

Finally, the decision result will be modified by de-mapping, and deinterleaving, and then passed to the channel decoder to obtain the final estimations of input signal $\hat{s}_1^{(i)}$ and $\hat{s}_2^{(i)}$.

4. SIMULATION RESULTS

In order to illustrate the basic concept of the proposed coded two-step receiver structure, we run the simulations simply based on a two user space-time block coded MIMO OFDM system case equipped with two transmit antennas for each user and two receive antennas. Each user data stream contains 256 symbols, for which a standard rate 1/2 and constraint length 3 convolutional code is used. In order to correct the subcarriers in deep fades, forward error correction and bit interleaving are used across the subcarriers. The QPSK signal mapping is employed at the transmitting stage. For the tones orthogonal to each other, the assumed bandwidth of 1MHz baseband is divided by the IFFT operation over each OFDM time slot after space-time block encoding. Moreover, an additional 22 cyclic prefix symbols are used as a guard interval after each data block. The data transmission is implemented simply over MIMO frequency selective channels with slow time variant fading, generated by the typical Jakes fading model [5] and 3-delay taps have been introduced into each sub-channel, i.e. a frequency-selective sub-channel tap length $L = 3$ and $\sum_{l=1}^{L} \sigma_l^2 = 1$, where σ_l^2 is the variance of the lth path. The channel fading is also simplified with an assumption of no correlation between different transmitting antennas of different users. Perfect knowledge of the channel state at the receiver is assumed. In order to keep equal signal power under the effect of channel coding, the complex white Gaussian noise was compensated by scaling by convolutional coding rate for normalization and the soft input Viterbi decoding scheme is used in this simulation.

Fig. 2 shows the comparison of system performance between the channel coding scheme and the normal scheme for linear MMSE interference cancellation and two-step processing respectively. The system is tested within quasi-static channel environments. The best performance is given by the coded two-step interference cancellation scheme. The coded two-step interference cancellation scheme over the range of SNR in the figure shows higher gradient of the frame error rate curve better than the other scheme, as a result, the ISI and MAI have been cancelled effectively by the two-step processing and coding correction. In this paper, we use the typical STBC scheme as

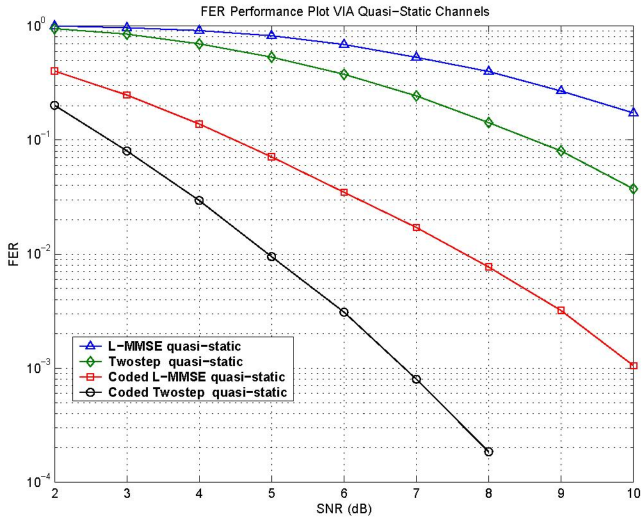

Fig. 2. FER performance comparison for quasi-static channels

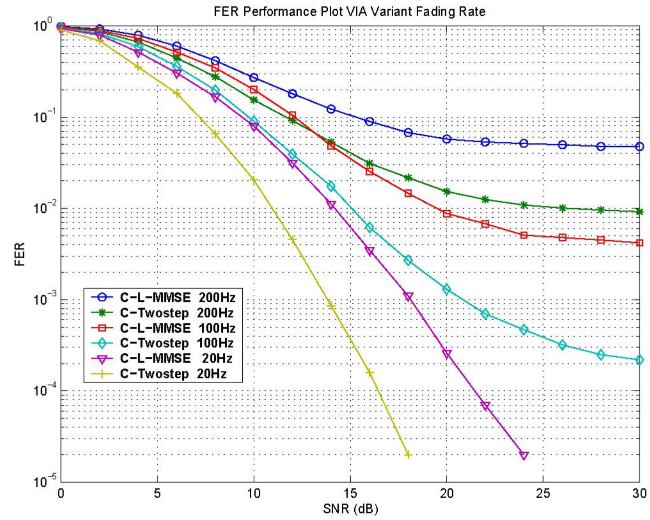

Fig. 3. FER performance comparison for different maximum Doppler frequency fading rates.

in [2] in order to attain double spatial diversity compared with normal MIMO transmission. Hence, following the explanations in [2], [3] and [7], this coded two-step scheme could almost achieve a diversity order of $2 \times (m - K + 1)$. In addition to the multiple transmit and receive antenna diversities, the frequency selective diversity of order L can also be gained by the effect of coding correction.

Secondly, we can also see that the performance degrades at higher SNR values with increasing maximum Doppler frequency which is shown in Fig.3. Recall that the channel is assumed to be quasi-static over two OFDM symbol periods in order to employ space-time block codes. This assumption will be violated in this case and the space-time block code and OFDM fails to keep their orthogonality between the antennas and the carriers which causes the error floor. However, the MAI and time variant interference are still suppressed effectively by the coding two-step scheme within a slow fading channel environment, e.g. 20Hz (Normalized Doppler frequency is 0.0055).

5. CONCLUSION

In this paper, we have addressed the design of a channel coded two-step interference cancellation receiver to cancel multiple access interference (MAI) in a multiuser MIMO wideband wireless communication system within a slow fading channel environment. In this approach, the transmitter uses space-time block codes and OFDM modulation, which are serially concatenated. Another approach would be to use space-frequency block codes and OFDM modulation to provide further robustness to the time-varying channel. The receiver is based on a two-step interference cancellation algorithm with error control coding techniques. The simulation results indicate that the proposed scheme could obtain substantial performance improvement in typical wireless communication environment with realizable computational complexity. By concatenating the transmitter with the half rate outer channel code, the proposed scheme obtained significant performance gain rather than the normal scheme.

6. REFERENCES

[1] X. Wang and H. V. Poor *Iterative (turbo) soft interference cancellation and decoding for coded CDMA* , IEEE Trans. on Communications, Volume 47, No.7, pp. 1046 - 1061, July 1999.

[2] S. M. Alamouti, *A simple transmit diversity technique for wireless communications*, IEEE J. Selected Areas Communications, Volume16, No. 8, pp. 1451 - 1458, October 1998.

[3] A. F. Naguib, N. Seshadri and A. R. Calderbank, *Application of space-time coding and interference suppression for high capacity and high data rate wireless system*, in proc. 32nd Asilomar Conf. Signals, System, and Computers, vol. 2, Pacific Grove, CA, pp. 1803 - 1810, November 1998.

[4] S. Suthaharan, A. Nallanathan and B. Kannan, *Space-Time coded MIMO-OFDM for high capacity and high data-rate wireless communication over frequency selective fading channels*, Mobile and Wireless Communications Network 2002, 4th International Workshop, pp. 424 - 428, September 2002.

[5] P. Dent, G. E. Bottomley and T. Croft, *Jakes fading model revisited*, Electronics Letters, Volume 29, No. 13, pp. 1162 - 1163, June 1993.

[6] P. L. Kafle, A. B. Sesay and J. McRory, *An iterative MMSE-decision feedback multiuser detector for space-time coded multicarrier CDMA system*, Electrical and Computer Engineering, 2004. Canadian Conference, Volume 4, pp. 2281 - 2286, May 2004.

[7] E. A. Fain and M. K. Varanasi, *Diversity order gain for narrowband multiuser communications with precombining group detection*, IEEE Trans. Commun., volume 48, No. 4, pp. 533 - 536, April. 2000.

[8] P. Schniter, *Low-complexity equalization of OFDM in doubly selective channels*, IEEE Transactions on Signal Processing, Volume 52, No. 4, pp. 1002 - 1011, April 2004.