Implementation and Testing of Super-Orthogonal Space Time Trellis Codes

Lai Wei and Oscar Takeshita
The Ohio State University

Parul Gupta, Weijun Zhu and Michael P. Fitz
The University of California Los Angeles

***Abstract*— In wireless mobile communication systems, antenna diversity is one of the most important techniques to improve the performance. Codes suitable for antenna diversity which achieve full diversity, full rate and good coding gains are preferred when there is a small number of parallel channels. A concatenated space-time block code and multiple trellis coded modulation (STBC-MTCM) scheme achieves this goal. An 8-state STBC-MTCM with two antennas at the transmitter and one antenna at the receiver is implemented with interleaver and channel estimation on the OSU/UCLA wireless narrowband testbed. The design is described in detail. The system hardware setup is briefly overviewed and simulation bench test results are also provided. During our bench tests, an error floor was observed at high SNR's. This study is a first attempt to quantify the limits of achievable performance of real implementations of space-time coding.**

I. Introduction

In wireless mobile communication system, diversity is one of the most important techniques to improve performance. It has been shown by *Telatar* in [1] and by *Foschini* and *Gans* in [2] that multiple antennas can greatly improve performance in a wireless communication system. Space-time coding is a commonly acceptable approach if the wireless communication system has a small number of parallel channels. The standard design criteria to construct a good space-time code for this case are presented in [3] and [4]. Research in space-time coding spans from its early form of delay diversity, *Alamouti*'s simple 2 by 2 block code [5] to sophisticated space-time trellis code (STTC) [3], space-time block codes (STBC) [6], [7] and space-time turbo codes [8].

STBC codes achieve full diversity with extremely low decoder complexity. However, simple decoding structures and coding gain are not compatible. Although there exist codes which achieve full diversity and coding gain, they are either rate-lossy or have a complicated decoding structure. Several researchers have proposed new techniques to construct improved high-rate space-time codes in [9], [10], [11] based on a concatenation of an orthogonal space-time block code and an outer M-TCM encoder. It has been shown that this kind of STBC-MTCM code achieves full rate, full diversity and coding gain with reasonably low complexity by exploiting the signal orthogonality.

In this paper, we focus on the implementation of Siwamogsatham and Fitz's STBC-MTCM on the forward link of the OSU/UCLA wireless testbed. Table I shows the key parameters of the forward link of our narrowband testbed.

TABLE I
Testbed forward link parameters

Parameters	Forward Link
Carrier Frequency (f_c)	220.5625MHz
Channel Bandwidth (Δ f)	4KHz
Symbol Rate ($1/T$)	3.2KHz
Frame Length (N_f)	150symbols
Doppler Shift ($f_D T$)	$\leq$ 1%

This system is well modeled with a frequency nonselective flat fading channel.

The paper is organized as follows. Section II reviews some important theory to design Siwamogsatham and Fitz's STBC-MTCM code and provides the method for channel estimation. Section III presents the system design of the forward link in the testbed, which includes frame structure, pilot symbol assisted modulation (PSAM) design and block interleaver. Section IV gives the implementation details and the simulation and bench test results. Section V concludes.

II. Theoretical Review

We discuss, in this paper, the implementation of the *Siwamogsatham* and *Fitz* 8-state STBC-MTCM with two transmit and one receive antennas on our testbed. This code uses QPSK constellation and achieves full-rate, full diversity and substantial coding gain. Fig.1 depicts the trellis diagram of

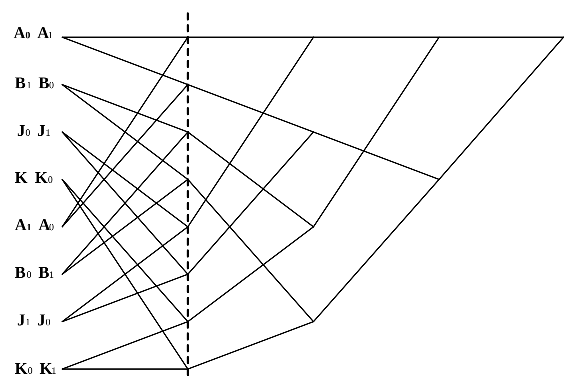

Fig. 1. 8-state STBC-MTCM for L_t=2 and L_r=1

this 8-state 2bits/symbol QPSK space-time code. An M-TCM scheme with multiplicity of 2 is used as the outer encoder. Four bits come in at every encoding instant so each state has 16 incoming and outgoing transitions. From the trellis diagram 1, there are only two transitions to different states, therefore, the outer M-TCM encoder has 8 parallel branches. Additionally, it can be seen that transition branches leaving from or arriving in each state are uniquely labelled with codewords from the same block code.

As mentioned before, two features used in the design this space-time code are an expanded orthogonal block space-time code and set partitioning. We start with the 2×2 orthogonal *Alamouti* code as the building subset. Other signal subsets can be formed by $A(s_0, s_1) \cdot G_i$, where G_i is $L_t \times L_t$ diagonal unitary matrix. It has been shown the following four subsets are sufficient for designing a good space-time code. A union of these signal subsets forms an expanded orthogonal block code.

$$A(s_0, s_1) = \begin{bmatrix} s_0 & s_1 \\ -s_1^* & s_0^* \end{bmatrix} \tag{1}$$

$$\begin{aligned} B(s_0, s_1) &= A(s_0, s_1) \cdot G_B \\ &= A(s_0, s_1) \cdot \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix} \\ &= \begin{bmatrix} s_0 & -s_1 \\ -s_1^* & -s_0^* \end{bmatrix} \end{aligned} \tag{2}$$

$$\begin{aligned} J(s_0, s_1) &= A(s_0, s_1) \cdot G_J \\ &= A(s_0, s_1) \cdot \begin{bmatrix} 1 & 0 \\ 0 & j \end{bmatrix} \\ &= \begin{bmatrix} s_0 & js_1 \\ -s_1^* & js_0^* \end{bmatrix} \end{aligned} \tag{3}$$

$$\begin{aligned} K(s_0, s_1) &= A(s_0, s_1) \cdot G_K \\ &= A(s_0, s_1) \cdot \begin{bmatrix} 1 & 0 \\ 0 & -j \end{bmatrix} \\ &= \begin{bmatrix} s_0 & -js_1 \\ -s_1^* & -js_0^* \end{bmatrix} \end{aligned} \tag{4}$$

Then we use the standard method to divide each of the four full-rank of block code subsets into 2 partitions with a cardinality of 8, e.g.,

$$A_0 = A(\pm 1, \pm 1), A(\pm j, \pm j) \tag{5}$$

$$A_1 = A(\pm 1, \pm j), A(\pm j, \pm 1) \tag{6}$$

It has been proved that this STBC-MTCM achieves full diversity in this way.

This concatenated STBC-MTCM code can be decoded by a Viterbi decoder conceptually. But it is not as simple as a traditional TCM because MTCM has multiple parallel transitions in each branch in the trellis to achieve higher rate with the same number of trellis states. The key idea for STBC-MTCM decoder is to combine the standard simplified ML decoding algorithm with the concept of signal partitions. Therefore, in order to achieve reduced complexity decoding, we shall partition a signal set assigned to parallel transitions into smaller signal partitions such that the standard simplified ML decoding algorithm can be directly applied in each smaller signal partition. The details of the efficient decoding are found [9]

A. Channel Estimation

Channel estimation is a critical part in any communication system. It is necessary to estimate the channel state information accurately to make space-time decoding reliable. We assume the channel is constant during a symbol period, but varies from symbol to symbol since slow fading exists in our system. We consider FIR Wiener filter for MISO channel estimation [12]. As shown in Fig.2, $p_l(k)$ is the pilot symbol

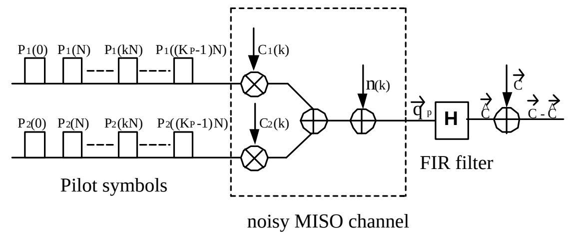

Fig. 2. MISO Channel Estimation

transmitted from antenna l at time instant kN_p where N_p is the pilot insertion period. $\vec{q_p}$ is the observation vector of $K_p \times 1$ where K_p is the number of taps for Wiener filter. $\vec{c}$ is the true channel gain and has dimension of $L_t(N_p - 1) \times 1$. $\vec{\hat{c}}$ is the estimated channel gain. H is the wiener filter which has dimension $L_t(N_p - 1) \times K_p$ and $\vec{\tilde{c}}$ is the estimation error vector. Since FIR filter is assumed, we have

$$\vec{\hat{c}} = H \cdot \vec{q_p}. \tag{7}$$

The MMSE estimator is

$$H = E[\vec{c} \cdot \vec{q_p}^H] E[\vec{q_p} \cdot \vec{q_p}^H]^{-1}. \tag{8}$$

For the space-time system model we have

$$\vec{q_p} = \Lambda_p \vec{c_p} + \vec{n_p} \tag{9}$$

where Λ_p is the pilot symbol matrix, $\vec{c_p}$ and $\vec{n_p}$ are the channel gain vector and the noise vector at the pilot symbol positions respectively. With this model and defining $Cov(\vec{c_p}) \equiv E[\vec{c_p} \cdot \vec{c_p}^H]$ and $Cov(\vec{c}, \vec{c_p}) \equiv E[\vec{c} \cdot \vec{c_p}^H]$ H is given as

$$H = Cov(\vec{c}, \vec{c_p}) \Lambda_p^H \left(\Lambda_p Cov(\vec{c_p}) \cdot \Lambda_p^H + N_0 I \right)^{-1}. \tag{10}$$

III. SPACE-TIME CODING SYSTEM DESIGN

The space-time scheme described above is implemented on the forward link of the OSU/UCLA testbed, which employs continuous transmission. PSAM is important to channel estimation, which will heavily affect the performance of space-time code. The use of an interleaver reduces or eliminates the memory of the channel and converts correlated fading (which is typical of slow fading) into independent fading. A Block interleaver is used in our space-time coding system.

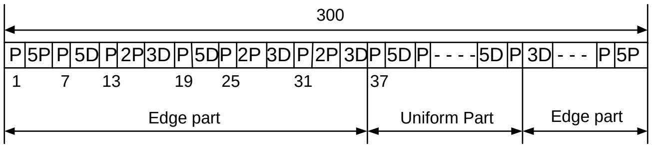

Fig. 3. Pilot Frame Design for OSU STC System. P represents Pilot and D represents Data

A. Frame structure and signaling

The space-time pilot frame is designed to have 300 symbols. The frame design is shown in Fig.3. 72 symbols are used for pilot symbols among 300 symbols space-time pilot frame, which include three kinds of pilots interspersed in the frame, i.e., uniform pilots, preamble/postamble pilots and replacement pilots. The replacement pilots derive their names from the fact that we can get more smoothness in the channel estimation error if we substitute L_t data symbols by L_t pilot symbols in the positions of these replacement pilots . Specifically we use N_p = 6 for the uniform part. The orthogonal pilot element (chosen from QPSK constellation) is shown below

$$P = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}. \tag{11}$$

Using orthogonal pilot symbols on each antennas was shown to be optimal in [13]. By optimizing the FIR Wiener filter for E_b/N_0 = 20dB and $f_D T$ = 1% we get a set of filter coefficients for both the uniform part and the edge part, which are stored at the receiver and used for channel estimation . More details on the pilot frame design are available in [12].

B. Modified block interleaver

The interleaver is another key component in coded modulation systems. A modified block interleaver is chosen for our space-time coding implementation for simplicity. Two parameters, i.e., depth and span, are important in a block interleaver design. The interleaver depth (D_{iv}) determines how far apart two adjacent source symbols are separated on the channel and the interleaver span (S_{iv}) determines how many consecutive source symbols experience different fading.

As shown in Fig.4, we use this modified block interleaver design for L_t = 2 case $(D_{iv} \times S_{iv} = 26 \times 9)$. From Fig.4(a), we notice that there are only 228 data symbols for a space-time pilot frame, therefore this table is not fully filled. We write the source symbols into the table following the pattern as shown in Fig.4(a) and then read them out row-wise and place them into the frame on the channel, which is shown as Fig.4(c). Hence, we find L_t aligned consecutive source symbols as a group will experience the same fading but the groups that are separated by more than D_{iv} symbol intervals experience near-independent fading. Therefore this modified block interleaver can be called group-wise block interleaver.

IV. Implementation

We will present studies of the performance of this STBC-MTCM code based on Matlab simulations and bench tests on the OSU/UCLA testbed.

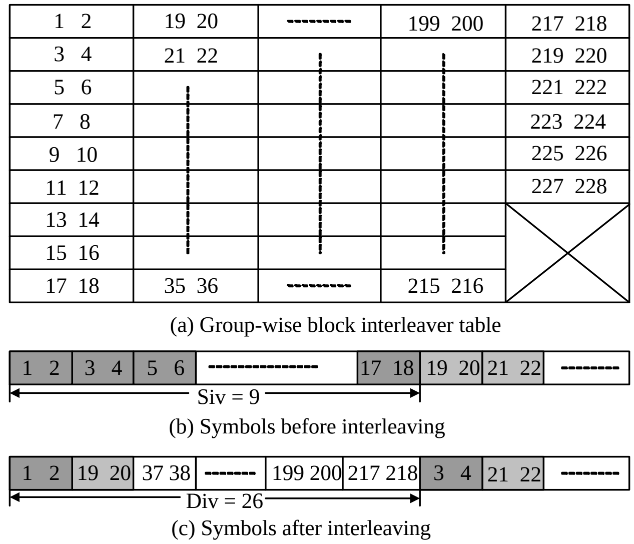

Fig. 4. Group-Wise Block Interleaver for STBC-MTCM System

A. Hardware Setup

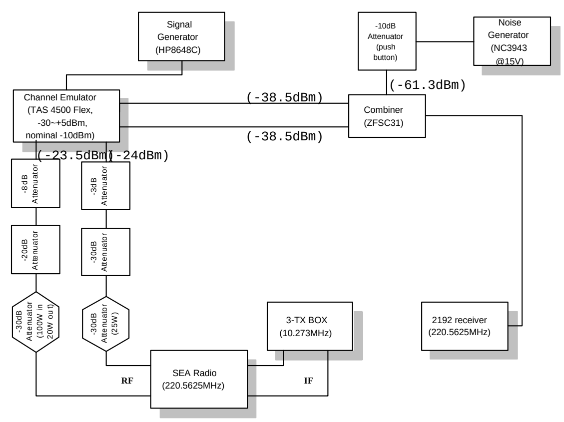

Fig. 5. Test Setup for Space-Time Coding System

Fig.5 shows the block diagram for the space-time coding test system with two transmit and one receive antenna. The transmitter has two parts, i.e., a multiple transmitter IF system and two radios. The single antenna receiver is the mobile unit (MU) with ADSP2192 fixed point processor. The mobile unit is designed to reflect an architecture that would be typical of a mobile unit in practice. This includes direct I/Q upconversion and downconversion and the associated degradations that occur is such implementations. The baseband data converters were COTS parts and were implemented with a DC block at the input.

B. Simulation Results

The Matlab simulation error performance for the 8-state STBC-MTCM code in a $2x1$ MISO system under different

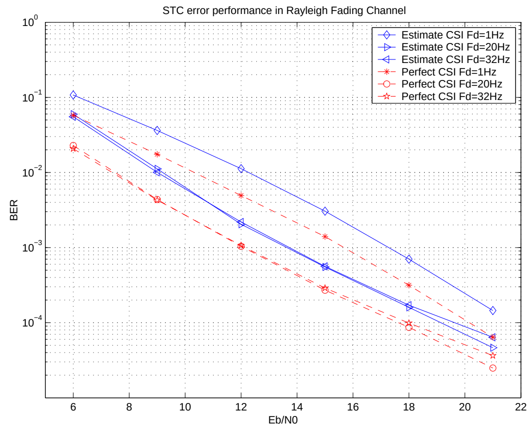

Fig. 6. Simulated Bit Error Rate for the 8-state STBC-MTCM. $L_t = 2, L_r = 1$

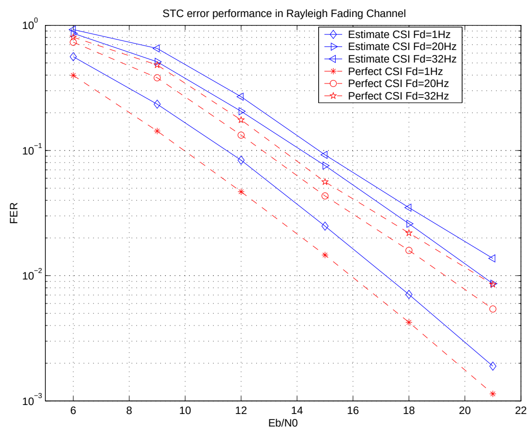

Fig. 7. Simulated Frame Error Rate for the 8-state STBC-MTCM. $L_t = 2, L_r = 1$

Doppler shifts $f_D T$ are provided in Fig.6 and Fig.7. The symbol rate is 3200symbols/sec. The designed space-time coding system has already been shown in Fig.1. However, pulse-shaping and matched filter have not been included in the simulation system. The simulated performance is evaluated in terms of the bit error rate (BER) and the frame error rate (FER) as the function of the signal-to-noise ratio (SNR). From Fig.6 and Fig.7, some conclusions can be drawn as follows:

- As we expect, space-time code with perfect CSI always has better performance than that with estimated CSI. The channel estimation error generally causes nearly $1.5 \sim 2db$ loss in SNR. This loss is due to the combination of the loss in throughput due to using PSAM and the excess noise in the estimates.
- Since the received signal strength changes relatively slowly under the smaller Doppler spread, it is not surprising to see that the space-time code with smallest Doppler spread $f_D = 1Hz$ has the best performance in forms of FER for either perfect CSI or estimated CSI. Therefore, the FER of space-time code depends on the Doppler spread. The more slowly the received signal strength changes, the better FER performance is achieved.
- However, we can notice that BER under $f_D = 1Hz$ is bigger than that under other Doppler spreads. This also can be explained by the relatively slowly changing in signal strength since there are many error bits in one error frame though the error frames for $f_D = 1Hz$ are less than for other Doppler spreads.
- It can be seen that the BER curves for $f_D = 20Hz$ and $f_D = 32Hz$ are close to each other at low SNR for both perfect CSI and estimated CSI. But when SNR is large, we still can find that the space-time code with smaller Doppler spread has better performance than that with bigger Doppler spread.

C. Benchtest Results

According to the definition of E_b/N_0, we get the following equation,

$$E_b/N_0 = \frac{P_s \times 1 \times \frac{1}{3200} \times \frac{1}{2}}{\frac{P_n}{4000}} = \frac{P_s}{P_n} \times \frac{5}{8} \qquad (12)$$

where P_s and P_n are measured band power values for signal and noise, respectively. 3200symbols/sec is the symbol rate on the testbed forward link. Code rate for both uncoded QPSK and space-time code is 2bit/symbol and signal bandwidth is 4KHz. After taking dB values to Eqn.12, we get the following E_b/N_0 calibration

$$E_b/N_0 = SNR - 2.04 = P_s - P_n - 2.04(dB) \qquad (13)$$

According to Fig.8, we can see for the AWGN case, space-time code achieves at least 2.5dB coding gain with respect to uncoded QPSK for BER below 10^{-5}.

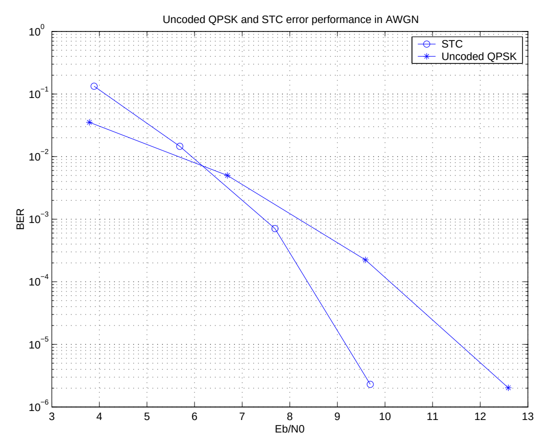

Fig. 8. Bit Error Performance for Uncoded QPSK and STC under AWGN Channel

In order to study the performance of the space-time code, we only calculate the error bits and the error frames based on transmitted space-time coding frames. Then we can get the error performance of space-time coding system under fading channels as following, As we can see from the Fig.9 and Fig.10,

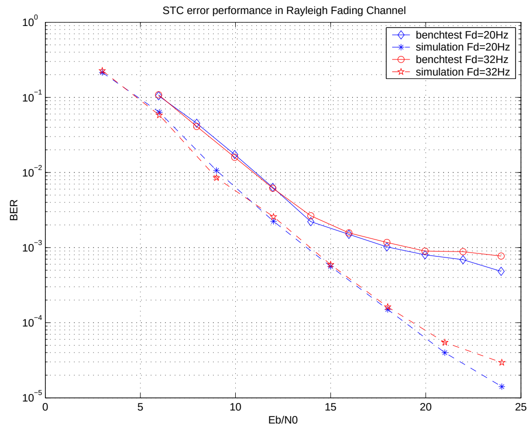

Fig. 9. Bit Error Performance for STC under Fading Channel

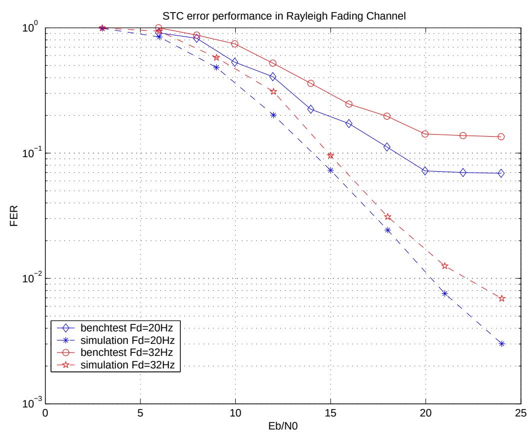

Fig. 10. Frame Error Performance for STC under Fading Channel

- Bench test results are close to Matlab simulation results at the low SNR.
- For both bench test results and Matlab simulation results, the bit error rate under $f_D = 32Hz$ and $f_D = 20Hz$ are close to each other. But we can notice the difference between them is existed in forms of frame error rate. The smaller f_D has better performance as we desired.
- It is very clear that error-floor exists in our space-time coding system. The error-floor might be caused by Intersymbol Interference (ISI) of the hardware (e.g. DC block in the receiver). We did a significant analysis of the processing chain, which we cannot present due to space limitations but found that the error floor that is observed is due to errors in the channel estimation caused by residual ISI. This ISI is caused primarily by the DC block in the data converters.

V. Conclusions

This paper presented an implementation of an advanced space-time coding scheme in a real-time testbed. The performance at baseband was optimized for short packet transmission and pilot symbol channel estimation. The most surprising result from the study was the susceptibility of space-time decoding to distortions in the radio.

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VI. Acknowledgement

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