Space-Time Coded OFDM for High Data-Rate Wireless Communication Over Wideband Channels

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I. INTRODUCTION

Recently there has been an increasing interest in providing high data-rate services such as video-conferencing, multimedia internet access and wide area network over wideband wireless channels. Wideband wireless channels available in PCS band (2 GHz) have been envisioned to be used by mobile (high Doppler) and stationary (low Doppler) units in a variety of delay spread profiles. This is a challenging task, given the limited link budget and severity of wireless environment, and calls for the development of novel robust bandwidth efficient techniques which work reliably at low SNRs.

To this end, we design a space-time coded orthogonal frequency division multiplexing (OFDM) modulated physical layer. This combines coding and modulation. Space-time codes were recently proposed for narrowband wireless channels [1, 2]. These codes have high spectral efficiency and operate at very low SNR (within 2-3 dB of the capacity). On the other hand, OFDM has matured as a modulation scheme for wideband channels [3, 4, 5]. We combine these two in a natural manner and propose a system achieving data rates of 1.5-3 Mbps over a 1 MHz bandwidth channel. This system requires 18-23 dB (resp. 9-14 dB) receive SNR at frame error probability of 10^{-2} with two transmit and one receive antennas (resp. two transmit and two receive antennas). As space-time coding does not require any form of interleaving, the proposed system is attractive for delay-sensitive applications.

II. THE SYSTEM MODEL

We consider a multiple antenna wireless communication system which is equipped with n transmit and m receive antennas. In practice, the number of transmit and receive antennas is constrained by the cost. We assume that a total bandwidth of F Hz is available which is divided into l overlapping subbands.

At each time t, a block of bits is the input to the space-time encoder. The output of encoder at time t is a codeword of the form

$$\mathbf{C}^t = C^t_{1,0}\cdots C^t_{n,0}C^t_{1,1}\cdots C^t_{n,1}\cdots C^t_{1,l-1}\cdots C^t_{n,l-1},$$

where $C^t_{i,k}$ belongs to a constellation such as M-PSK or 2^b-QAM. The superscript t denotes the time throughout this paper. OFDM modulation is used to modulate

$$C^t_{i,0}C^t_{i,1}\cdots C^t_{i,l-1}$$

for $i = 1, 2, \ldots, n$ and the resulting signal is transmitted through transmit antenna i at time t. We emphasize that all these signals are transmitted simultaneously. We append a cyclic prefix to each OFDM frame to avoid any ISI possibly due to the delay spread of the channel. We assume frame synchronization as well as sample-clock synchronization between the transmitter and the receiver.

We assume that the fading is quasi-static, i.e., it remains constant during the transmission of an OFDM frame and it changes from a frame to other. This is a reasonable assumption given the chosen system parameters. The signal at each receive antenna is a noisy version of the superposition of the faded versions of the n transmitted signals. The received signal at each receive antenna is sampled at a rate of F Hz and cyclic prefix is stripped from each frame. These samples form sufficient decision-statistics and are then fed to an OFDM demodulator [6]. The output of OFDM demodulator for receive antenna j, for $j = 1, 2, \ldots, m$, is given by:

$$R^t_{j,k} = \sum_{i=1}^{n} H^t_{i,j,k}C^t_{i,k} + N^t_{j,k} \qquad \text{for } k = 1, 2, \ldots, l-1,$$

where $H^t_{i,j,k}$ are the frequency response of the channel from the i-th transmit antenna to j-th receive antenna, at k-th multicarrier frequency (kF/l), and, $N^t_{j,k}$ are independent samples of a Gaussian random variable with variance N_0. In the presence of perfect channel state information (CSI), maximum likelihood (ML) decision at the decoder amounts to computing

$$\hat{\mathbf{C}}^t = \underset{\mathbf{Q}}{\operatorname{argmin}} \sum_{j=1}^{m}\sum_{k=0}^{l-1} |R^t_{j,k} - \sum_{i=1}^{n} H^t_{i,j,k}Q_{i,k}|^2,$$

where the minimization is over all possible codewords $\mathbf{Q} = \{Q_{i,k}\}$ of the space-time code used in transmission. As the space-time codes considered in this paper are trellis-based [1], the above metric can be computed using the Viterbi algorithm. In the absence of channel state information, the decoder must estimate the channel states using pilot symbols. In this paper, it is assumed that the perfect channel state information is available to the decoder.

We emphasize that the transmission from all transmit antennas is simultaneous and uses the entire bandwidth as compared to some other proposed schemes where

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transmission from different antennas are separated in time and/or frequency. Multiplexing transmission from transmit antennas in time and/or frequency provides diversity for the aforementioned schemes, whereas our method exploits spatial diversity through space-time coding with no bandwidth penalty.

Space-time codes were designed to guarantee a target diversity and coding gain for *quasi-static*, *flat-fading* narrow-band channels [1, 2]. It can be shown that in the wideband system model considered in this paper, target diversity and coding gain of space-time codes are preserved [7]. Furthermore, frequency-selective fading can only improve the performance of space-time codes. This provides robustness under a variety of channel characteristics and mobility conditions.

III. SIMULATION RESULTS

In this section, we provide simulation results for space-time coded OFDM scheme. In these simulations, the Jakes model is adapted for fading [8]. All multipaths undergo independent Rayleigh fading and are assumed to have equal average power. The maximum Doppler frequency is 200 Hz. In these simulations the available bandwidth is 1 MHz and $l = 256$ carrier tones are used for OFDM modulation. These correspond to a subchannel separation of 3.9 KHz and OFDM frame duration of $256\mu s$. To each frame, a cyclic prefix of $40\mu s$ duration is added to combat the effect of intersymbol interference.

For comparing space-time coded OFDM technique, we use the OFDM scheme of Cimini *et. al* [4]. This scheme combines transmit diversity with OFDM modulation and provides comparable performance to similar schemes known in the art. In this scheme, a RS code is employed to encode the symbols across the frequency. These encoded symbols are modulated by OFDM carrier tones. In an n transmit antenna system, these tones are clustered into n smaller blocks and each block is transmitted over a separate antenna. At the receiver, symbol-by-symbol decisions are made for the modulated symbols. These symbol decisions along with their signal strength are the input to a RS decoder capable of errors-and-erasures decoding.

For space-time coded OFDM, we use a trellis based 16-state 4-PSK space-time code shown in Figure 1. Each codeword in this code corresponds to a path of length 256 in the trellis which can be chosen by a block of 512 bits. To exploit the benefits of the Viterbi decoding, we require that at the beginning and the end of each path corresponding to a codeword, the trellis encoder be in the zero state. Thus, in each block of 512 bits input to the encoder, we set the last four bits to zero to ensure that the encoder ends in the zero state. A more detailed description of code can be found in [1]. Note that this code requires two transmit antennas (with optional multiple receive antennas) and guarantees a diversity of $2m$ for m receive antennas. With this code, the spectral efficiency of our scheme is $2 \times \frac{256}{296} \times \frac{508}{512} = 1.72$ bits/sec/Hz.

We may also use an outer (72, 64, 9) RS code over GF(2^7). In that situation, a codeword corresponds to $7 \times 72 = 504$ bits. We keep 4 bits in a block uncoded to form an auxiliary channel and set the last 4 bits to zero to ensure that the space-time encoder ends in the zero state. With this concatenated code, our scheme has a spectral efficiency of $2 \times \frac{256}{296} \times \frac{504}{512} \times \frac{64}{72} = 1.514$ bit/sec/Hz.

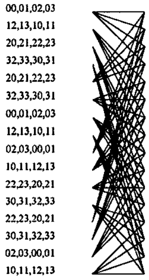

Figure 1: Trellis-section for 16-states, 4-PSK, 2 bits/sec/Hz space-time code

Note that in Cimini's scheme, SNR required to achieve a targeted probability of error can be reduced to some extent by providing more error-protection by RS code at the cost of reducing user data-rate. On the other hand, higher order constellation can be used to achieve higher data rate at the expense of increased SNR requirement. These trade-offs among the choices of error protection, signal constellation, and data-rates make a direct comparison between space-time coded and RS coded OFDM schemes difficult. In this paper, we consider two cases: First, we keep signal constellation the same (4-PSK) for both scheme and compare their performance. In the second set of results, we compare the performance, when both schemes have almost the same data-rate. Comparisons will be made using flat fading and two ray models for the subchannels between each pair of transmit and receive antennas. Delay spreads of $5\mu s$ and $40\mu s$ are considered. The aforementioned OFDM modulation/demodulation parameters are used for both schemes.

A. Performance for 4-PSK constellation

Following [4], for RS coded OFDM scheme, we use a rate 1/2 Reed-Solomon (RS) code to encode the 4-PSK symbols across the frequency. We used a (64, 32, 33) RS code over GF(2^8). A (64, 32, 33) RS codeword is $64 \times 8 = 512$ bits or 256 4-PSK symbols long. At the receiver, symbol-by-symbol decisions along with their signal-strength measurements are the input to the RS decoder. Sixteen RS symbols with the least signal strengths are declared erasures. Therefore, the RS decoder can correct up to 8 additional symbol errors using errors-and-erasures decoding. Note that this scheme has a spectral efficiency of $2 \times \frac{256}{296} \times \frac{32}{64} = 0.865$ bit/sec/Hz. This is about half the spectral efficiency of space-time coded OFDM scheme.

In Figure 2-4, we provide performance curves for these schemes using two transmit and one receive antennas. In all these plots, signal-to-noise ratio (SNR) denotes the average energy per symbol divided by one sided noise power

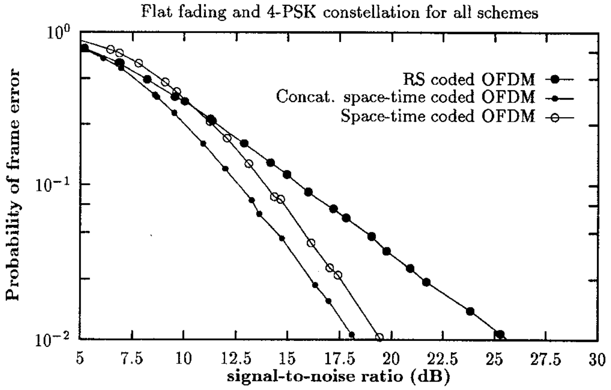

Figure 2: RS coded OFDM scheme depends on the frequency selectivity of the channel to gain diversity while space-time coded OFDM scheme has a guaranteed diversity regardless of the frequency selectivity. Space-time coded OFDM scheme outperforms the RS coded OFDM scheme by 6 dB despite having twice the bandwidth efficiency.

spectral density N_0. We compare various schemes at a frame error probability of 10^{-2}.

First, Figure 2 shows the performance of various schemes in a flat fading environment. At frame error probability of 10^{-2} our scheme outperforms the RS coded scheme by more than 6 dB while providing twice the data rate. In a flat fading environment, if the path gain from one of the transmit antennas to the receive antenna is small in magnitude, all the tones transmitted by this antenna will have very small signal strength. Therefore after symbol-by-symbol decisions are made, a large fraction of the symbols transmitted from this antenna will be in error. This is beyond the error-correction capability of the RS code. Our scheme performs well in such a situation because space-time codes are designed to provide diversity regardless of the frequency selectivity of the channel.

Next, we model the channel corresponding to each pair of transmit and receive antennas by a two-ray equal-power delay profile, where the delay spread between the two rays is 5μs. Figure 3 shows performance curves under this assumption. We observe that the performance of the RS coded OFDM scheme improves partially due to the frequency selectivity available in the channel. At this delay spread, the RS coded OFDM scheme performs better than our scheme by 6 dB. Note that our scheme has twice as much bandwidth efficiency. The performance of our scheme can be further enhanced by using encoders having a larger number of states without reducing the bandwidth efficiency. Another option is to concatenate space-time code with the (72, 64, 9) RS code described above, which can reduce required SNR further by 3 dB at the expense of decrease in the bandwidth efficiency by a factor of 0.888.

When the delay spread becomes large, a degradation

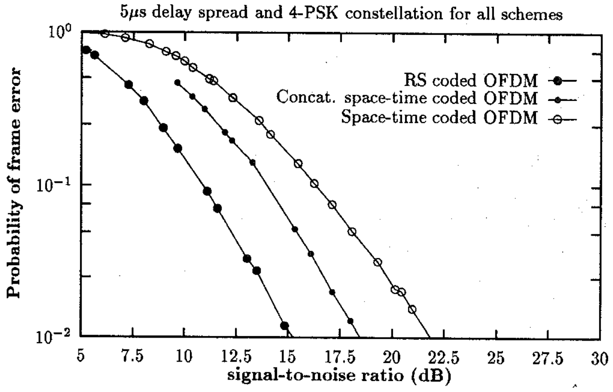

Figure 3: At 5μs, the delay is just right not to cause significant correlation among the signal strengths of RS symbols in a codeword and to provide frequency selectivity. RS coded OFDM scheme requires 6 dB less SNR although it transmit at only half the data rate of our scheme.

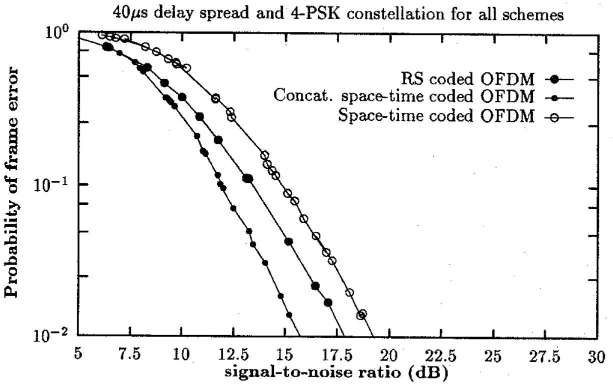

Figure 4: A delay spread of 40μs causes significant correlation among the signal strengths of RS symbols in a codeword and reduces the diversity gain provided by RS code. Space-time coded OFDM scheme maintains its diversity and performs close to RS coded OFDM scheme at twice the data rate.

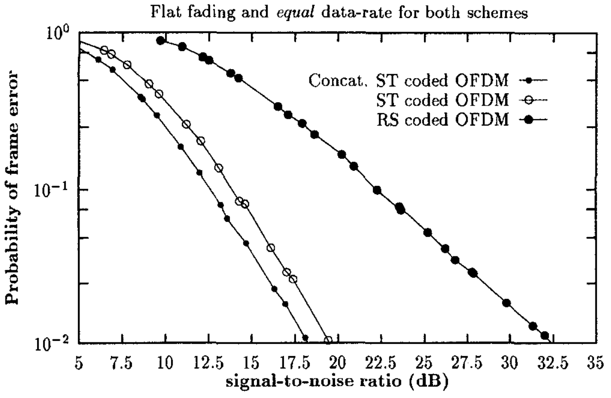

Figure 5: For the same bandwidth efficiency, space-time coded OFDM scheme performs RS coded OFDM scheme by more than 12 dB. Space-time codes provide guaranteed diversity even in the flat fading.

is observed in the performance of the RS coded OFDM scheme, whereas the performance of our scheme improves. We will provide explanation for these phenomena in [7]. Figure 4 shows performance curves for a $40\mu s$ delay spread. As can be seen, at $40\mu s$ delay spread, compared to the RS coded OFDM scheme, our scheme requires only 1.5 dB more SNR to transmit at twice the data rate. By using the outer code, our scheme outperforms the RS coded OFDM scheme by 2 dB, while having 1.75 times more bandwidth efficiency.

Note that the performance of our scheme only improves when the delay spread is increased, while the RS coded OFDM scheme eventually performs worse than the performance in flat fading case. Indeed, the required SNR for our scheme varies by at most 3 dB for a wide range of delay spreads. The corresponding variation for the RS coded OFDM scheme is more than 10 dB. However, in the cases described above, our scheme requires more SNR (while providing twice the data-rate) than RS coded OFDM, and it is desirable to compare both schemes at the same data-rate also.

B. Performance at same data-rate

In order to increase the spectral efficiency of the RS coded OFDM scheme, we use an 8-PSK constellation with rate 2/3 RS code applied across the symbols in frequency [4]. We choose a (64, 42, 23) RS code over GF(2^6). This codeword corresponds to $6 \times 64 = 384$ bits or $2 \times 64 = 128$ 8-PSK symbols. Therefore, for each OFDM frame, which is 256 8-PSK symbols long, we need two RS codes to encode the data. We use first halves of 128 8-PSK symbols transmitted from each transmit antenna to form one RS code and second halves of the transmitted symbols to form other. This grouping of symbols into the RS code maximizes diversity derived from multiple transmit antennas. For errors-and-erasure decoding, we use 10 erasures

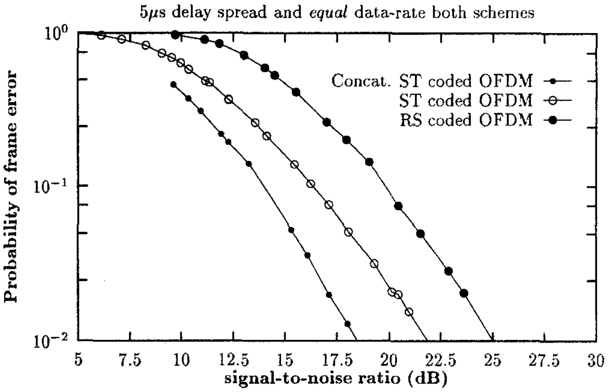

Figure 6: In presence of multipaths, frequency selectivity of channel is exploited by the RS coded OFDM scheme and its performance improves significantly. However, it still performs worst than the space-time coded OFDM.

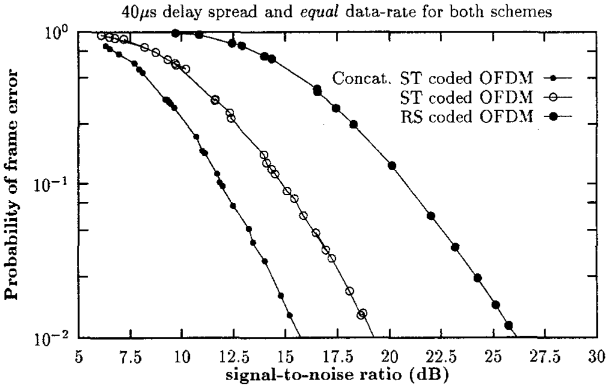

Figure 7: Significant correlation among the signal strengths of RS symbols at a $40\mu s$ delay reduces the diversity gain provided by RS code. Space-time coded OFDM maintains its performance causing the SNR gap between two scheme to go up to 7 dB.

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based on the signal strength. Therefore, RS decoder can correct up to 6 additional symbol errors. In this set-up, the RS coded OFDM scheme has a spectral efficiency of $3 \times \frac{256}{296} \times \frac{42}{64} = 1.70$ bit/sec/Hz, which is almost equal to the spectral efficiency of our scheme (1.72 bits/sec/Hz).

In Figures 5-7, we compare the performance of space-time coded OFMD scheme with the above described RS coded scheme. Once again, these results are for two transmit and one receive antennas. First, Figure 5 shows the performance in a flat fading environment. As can be seen, in flat fading environment, the performance of RS coded OFDM scheme deteriorates significantly and it requires 12 dB more SNR than our scheme at the probability of frame error 10^{-2}. However, if the channel between a transmitter and a receiver is frequency selective, the performance of RS coded OFDM improves significantly. Nevertheless, even for the favorable delay spread of $5\mu s$, the SNR gap between RS coded OFDM scheme and our scheme is a significant 3 dB (see Figure 6). As explained above, for larger delay spreads, the RS coded OFDM scheme starts showing a degradation in performance and at 40μs, the difference between SNR required by the RS coded OFDM scheme and our scheme goes up to 7 dB. Thus for equal data-rates, space-time coded OFDM scheme always outperforms RS coded OFDM scheme. Reduction in the required SNR depends on the frequency selectivity of the channel.

The required receive SNR for both schemes can further be reduced by using more receive antennas. Typical gains in using two receive antennas instead of one receive antenna are about 9-10 dB [7]. Performance trends for the two receive antennas are similar to those observed here for one receive antenna. In particular, our scheme continues to be robust when two receive antennas are used.

IV. Conclusions

In this paper, we described space-time coded OFDM scheme for providing high data-rate wireless communication over wideband channels. We presented simulation results for a 4-PSK 16-state space-time coded OFDM system and compared its performance to the RS coded OFDM scheme of [4]. We showed that the proposed scheme is capable of reliable transmission at relatively lower SNRs in a variety of delay profiles making it a robust alternative.

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