Robust Image Transmission over MIMO Space-Time Coded Wireless Systems*

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ABSTRACT

We present in this paper an integrated robust image transmission scheme using space-time block codes (STBC) over multi-input multi-output (MIMO) wireless systems. First, in order to achieve an excellent error resilient capability, multiple bitstreams are generated based on wavelet trees along the spatial orientations. The spatial-orientation trees in the wavelet domain are individually encoded using SPIHT. Error propagation is thus limited within each bitstreams. Then, Reed-Solomon (R-S) codes as forward error correction (FEC) are adopted to combat transmission errors over error-prone wireless channels and to detect residual errors so as to avoid error propagation in each bitstream. FEC can reduce the bit error rates at the expenses of increased data rate. However, it is often difficult to design an optimal FEC scheme for a time-varying multi-path fading channel that may fluctuate beyond the capacity of the adopted FEC scheme. Therefore, in order to overcome such difficulty, we propose an approach to alleviate the effect of multi-path fading by employing the STBC for spatial diversity with assumption that channel state information (CSI) is perfectly estimated at the receiver. Experimental results demonstrate that the proposed scheme can achieve much improved performance in terms of PSNR over Rayleigh flat fading channel as compared with a wireless system without spatial diversity.

Keywords: MIMO, space-time codes, wavelet tree coding, SPIHT, robust image transmission, multi-path fading

1. INTRODUCTION

Growing demands for better quality of service (QoS) by the mobile device users, such as high data rate and/or high quality multimedia services beyond conventional voice communication, pose significant challenges for service providers. Various wireless systems, such as multi-input multi-output (MIMO) wireless systems, have been developed in order to meet these increasing demands. However, mobile wireless networks with the high channel error rates resulting from time-varying multi-path fading still remain as significant challenges for reliable multimedia communication.

The error resilience techniques [1] [2] at the source coding end have been proven very successful to combat the transmission error with good trade-off in increased error robust capability and reduced compression efficiency. The error resilient tools implemented at the decoder ends usually can detect and localize errors so as to prevent the loss of correctly received data due to error propagation.

However, the error resilient tool itself cannot guarantee high quality multimedia service at high channel error rates. Hence, in order to achieve more reliable transmission of image and video over mobile wireless networks, forward error correction (FEC) is commonly adopted to combat transmission errors over error-prone channels. FEC [3] [4] can reduce the bit error rates at the expenses of increased data rate. However, it is often difficult to design an optimal FEC scheme for a wireless channel that may fluctuate beyond the capacity of the adopted FEC scheme.

Without any extra cost of data rate, space-time coding [5] [6] [10] [11] based on MIMO system has recently emerged as one of the most prominent techniques in order to reduce the bit error rates from multi-path fading characteristics in mobile wireless networks. The core idea of space-time coding is to maximize diversity using multiple spatially distributed antennas so as to improve the signal-noise ratio (SNR) with assumption that channel state information is

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perfectly estimated at the receiver. Alamouti [5] discovered a remarkable space-time block coding (STBC) that shows very simple and linear processing for transmission with two antennas.

In this research, we develop an integrated robust image transmission scheme using space-time block codes (STBC) over multi-input multi-output (MIMO) wireless systems. First, multiple bitstreams are generated based on wavelet trees along the spatial orientations in order to achieve an excellent error resilient capability of the compressed image. Then, Reed-Solomon (R-S) codes as forward error correction (FEC) are adopted to combat transmission errors over error-prone channels and to detect residual errors so as to avoid error propagation within each bitstream. Finally, we employ the STBC to maximize the spatial diversity to reduce the effect of multi-path fading without extra cost of data transmission rate.

The rest of this paper is organized as follows: In Section 2, an overall system description of the proposed scheme is given. We will also discuss both multiple wavelet tree coding and space-time block codes. In Section 3, experimental results are reported to demonstrate that the proposed scheme indeed is able to perform significantly better than the system without exploring the spatial diversity. Section 4 concludes this paper with summary and discussion.

2. SYSTEM DESCRIPTION

The proposed robust image transmission system over MIMO is shown in Figure 1. At the encoder side, a given image is hierarchically decomposed by discrete wavelet transform (DWT). The spatial-orientation trees in the wavelet domain are individually encoded using SPIHT to achieve an improved error resilient capability. Reed-Solomon (R-S) codes as FEC are added to combat transmission errors over error-prone channels and to detect residual errors so as to avoid error propagation in each bitstream. The generated multiple bitstreams are modulated as transmission signals. Finally, these signals are coded by STBC to fully maximize the spatial diversity, and then transmitted over Rayleight flat fading channel. At the decoder side, the received signals are detected by maximum-likelihood (ML) detection with CSI and demodulated. Bit errors are detected and corrected with R-S decoding and finally, the transmitted image is reconstructed by inverse multiple SPIHT decoding and inverse DWT.

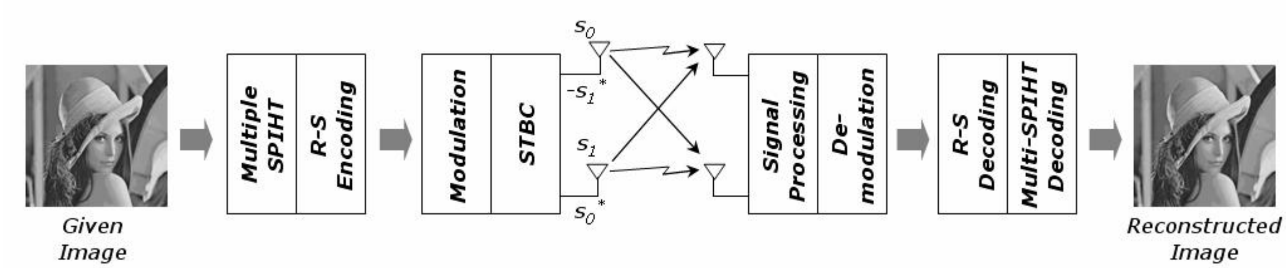

Figure 1: Illustration of the proposed robust image transmission system.

2.1 Multiple Wavelet Tree Coding

SPIHT is a state-of-the-art image compression algorithm and generates an embedded bitstream that achieves best trade-off between complexity and performance. Since the bitstream is progressive, rate change can be made easily and instantaneously by dropping packets either at the source or at the intermediate nodes. Therefore, SPIHT has nice properties in bit-rate adaptation for mobile wireless applications. However, the SPIHT bitstream is fragile to the channel errors; one bit error may cause the sequential bits successively received becoming unusable and being discarded. Hence, multiple wavelet tree coding is applied to produce multiple bitstreams so as to enhance error resilience capability by limiting the error propagation cause by the nature of the embedded coding. There is a direct relationship between wavelet coefficients and what they represent in the image content for each description [7].

The left of Fig. 2 is the spatial orientation tree structure proposed by Said et al [8]. This wavelet tree is rooted at the lowest frequency subband. Each node in the tree has either no descendants or four offspring grouped in 2×2 adjacent coefficients. If all coefficients in the tree are grouped together, they constitute a square block of data as shown in the right of Fig. 2. These data are the frequency components for a specific image area with the same block size at the corresponding position. As a result, one single tree corresponds solely to one image block.

For each wavelet tree, the SPIHT algorithm [8] can be employed to encode it independently and to generate one bitstream. It has been shown [9] that such a spatial orientation tree structure can improve data reception at the receiving end. In the case of BSC channels, suppose the BER ε is given and there are a total of S bits to transmit. When L multiple bitstreams are formed by the spatial orientation SPIHT structure, the probability of correctly receiving the first k consecutive bits in each bitstream will be

$$p(k) = \begin{cases} (1-\varepsilon)^k \times \varepsilon & 0 \le k \le S/L \\ (1-\varepsilon)^k & k = S/L \end{cases} \tag{1}$$

So the mean value of k is

$$m_L = \sum_{k=0}^{S/L} k \times p(k) \tag{2}$$

Therefore, the expectation of the total correctly received bits that can be used in decoding will be

$$R = L \times m_L \tag{3}$$

In general, m_L is less than m_1 but m_L approaches to m_1 when $S/L >> 1/\varepsilon$. That is, in the limit case, the total number of correctly received bits in L bitstreams is approximately L times the number of correctly received bits when using a single bitstream. Error resilient capability is increased in proportional to the number of wavelet trees while coding efficiency may be decreased due to the generation of multiple bitstreams.

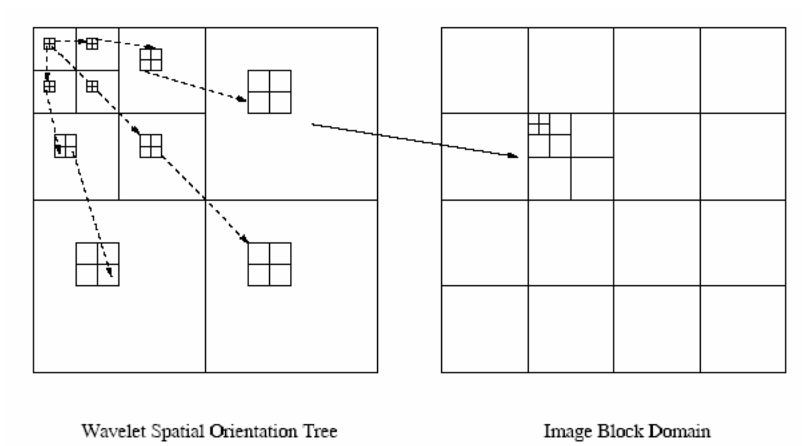

Figure 2: Relationship of wavelet tree and its corresponding image content

In this study, a given image is divided into 16 blocks in image block domain, thus 16 wavelet trees are independently encoded by SPIHT algorithm [8]. Then, R-S codes are added to each bitstreams in order to combat bit errors and detect residual errors so as to limit the error propagation cause by the nature of the embedded coding. Finally, the multiple bitstreams are inserted into STBC to fully maximize the spatial diversity.

2.2 Space-Time Block Codes

In this section, we shall review the space-time block codes (STBC) proposed by Alamouti [5]. In this study, we used 2 transmit and 2 receive antennas for transmitting the SPIHT compressed multiple bitstreams. We assumed that the channel is Rayleigh flat fading with a slow fading model. The channel matrix H is 2×2 matrix whose entries form an i.i.d. Gaussian collection with zero-mean, independent real and imaginary parts, each with variance 1/2.

Figure 3 shows the STBC MIMO wireless system equipped with two transmit antennas and two receive antennas. The encoding and transmission sequence of the information symbols for this configuration are shown in Table I. Table II defines the channels between transmit and receive antennas and Table III defines the notation for the received signal at the two receive antennas.

In particular, the received signals at the two receive antennas are defined as:

$$\begin{aligned} r_0 &= h_0 s_0 + h_1 s_1 + n_0 \\ r_1 &= -h_0 s_1^* + h_1 s_0^* + n_1 \\ r_2 &= h_2 s_0 + h_3 s_1 + n_2 \\ r_3 &= -h_2 s_1^* + h_3 s_0^* + n_3 \end{aligned} \quad (4)$$

where n_0, n_1, n_2, and n_3 are complex random variables representing receiver thermal noise and interference. The signal processing in Figure 3 reconstructs the following two signals that are sent to the maximum likelihood (ML) detector:

$$\begin{aligned} \tilde{s}_0 &= h_0^* r_0 + h_1 r_1^* + h_2^* r_2 + h_3 r_3^* \\ \tilde{s}_1 &= h_1^* r_0 - h_0 r_1^* + h_3^* r_2 - h_2 r_3^* \end{aligned} \quad (5)$$

Choose s_i for signal s_0 and s_1 iff

$$\begin{aligned} d^2(\tilde{s}_0, s_i) &\le d^2(\tilde{s}_0, s_k) \\ d^2(\tilde{s}_1, s_i) &\le d^2(\tilde{s}_1, s_k) \end{aligned}, \qquad \forall\ i \ne k \quad (6)$$

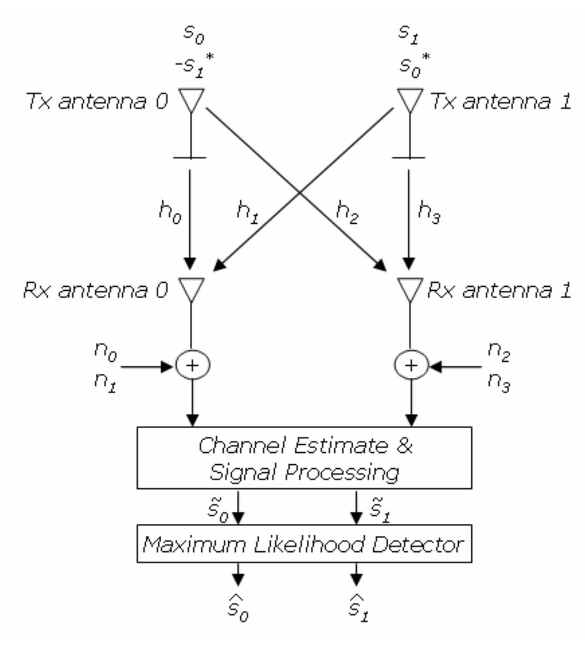

Figure 3: MIMO system with two transmit and receiver antennas.

Table I. The encoding and transmission sequence over 2×2 MIMO system

	Antenna 0	Antenna 1
Time t	s_0	S_1
Time t + T	$-s_1^*$	s_0^*

Table II. The definition of channels between the transmit and receiver antennas

	Rx Antenna 0	Rx Antenna 1
Tx Antenna 0	h_0	H_2
Tx Antenna 1	h_1	H_3

Table III. The notation for the received signals at the two receive antennas

	Rx Antenna 0	Rx Antenna 1
Time t	r_0	R_2
Time t + T	r_1	R_3

Figure 4 describes the procedure from multiple bitstreams generated in section 2.1 to STBC. At a given symbol period, if BPSK (1 [bit/symbol]) is used for modulation, first two digits (a_1 and a_2) are modulated as two signals (s_0 and s_1). Then, two signals are simultaneously transmitted from the two antennas. As described in Table I, the signal transmitted from antenna zero is denoted by s_0 and from antenna one by s_1. During the next symbol period, signal ($-s_1^*$) is transmitted from antenna zero, and signal s_0^* is transmitted from antenna one where * is the complex conjugated operation. With the assumption that fading is constant across two consecutive symbols and channel state is perfectly estimated at the receiver, the ML decoder can detect the transmitted signals with less error as compared with no diversity system.

Therefore, the robust image transmission of the proposed system is accomplished by coherent integration: (i) multiple bitstreams for limiting error propagation, (ii) R-S codes for correcting and detecting bit errors, and (iii) STBC for combating multi-path.

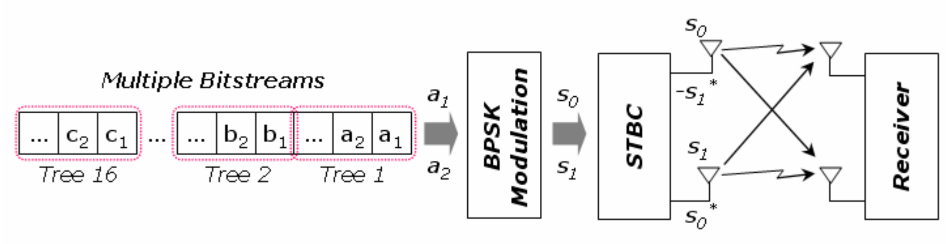

Figure 4: Procedure from multiple bitstreams to STBC.

3. EXPERIMENT RESULTS AND DISCUSSION

In this research, we first conduct experiments to demonstrate the diversity gain through STBC. Figure 5 shows the BER performance of coherent BPSK in Rayleigh flat fading. For fair comparison, we assume that the total transmit power from the two antennas for the STBC is the same as the transmit power from the single transmit antenna. It is also assumed that the amplitudes of fading from each transmit antenna to each receive antenna are mutually uncorrelated Rayleigh distributed. We further assume that the average signal powers at each receive antenna from each transmit antenna are the same. We also assume that the receiver has perfect knowledge of the channel. The performance comparisons in average BER as shown in Figure 5 have been obtained with 500,000 channel realizations.

Then, we conduct experiments on the 512×512 gray-scale Lena image to demonstrate the PSNR gains of MIMO wireless systems over single-input-single-output (SISO) wireless systems. For a given image, wavelet tree coding is employed to generate 16 bitstreams (0.5/16 bpp for each bitstream) with total coding rate 0.5 bpp. R-S (32,28) codes are employed to combat the bit errors. Figure 6 shows the reconstructed average PSNR with the ratio of transmit power (summed across two transmit antennas) to the noise variance. The results are obtained by averaging 100 trials for each channel condition. From this experiment, comparing with system without diversity (one antenna is equipped at transmit and receiver), diversity system (2×1 or 2×2 MIMO system) can achieve excellent performance improvement over SISO systems. For example, at 5[dB] (total power to the noise variance), the PSNR of 2×2 diversity system outperforms the system without diversity by about 20 [dB]. Figure 7 shows reconstructed example images received by system without diversity and the MIMO system with 2×2 STBC at 12.5[dB], 15[dB], and 17.5[dB] (total power to the noise variance), respectively.

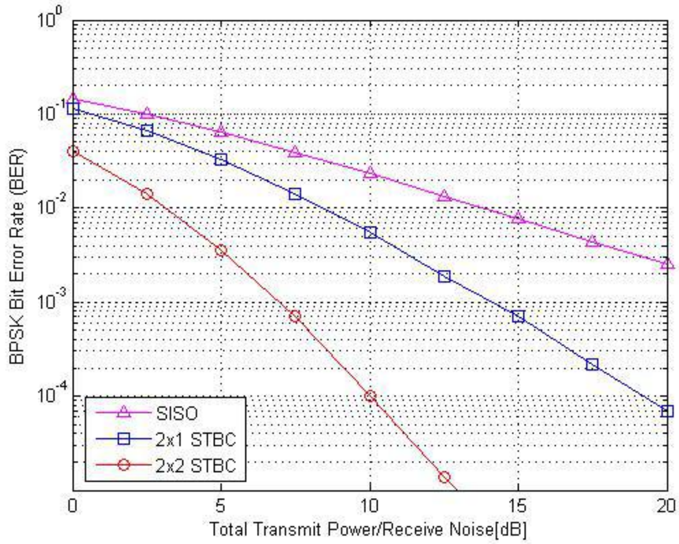

Figure 5: BER performance of coherent BPSK in Rayleigh flat fading channel.

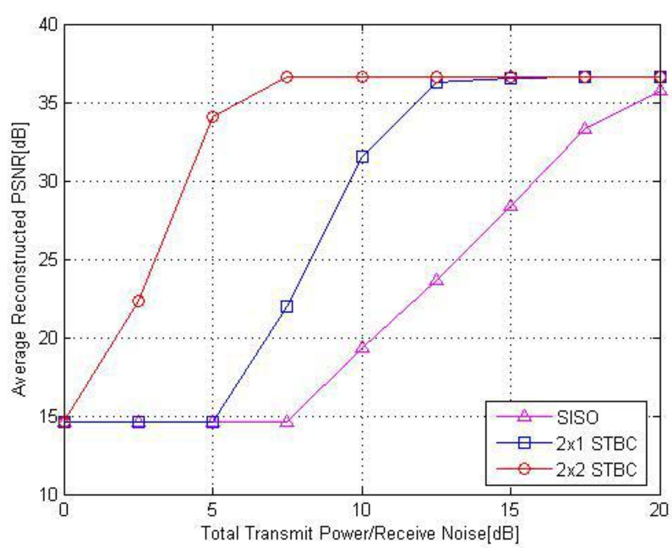

Figure 6: PSNR gain of MIMO wireless systems in Rayleigh flat fading channel.

4. CONCLUSION

In this paper, we have described an integrated robust image transmission scheme using space-time block codes (STBC) over multi-input multi-output (MIMO) wireless systems. The robustness of the proposed system is achieved by coherent integration of multiple bitstream coding and transmission, R-S forward error correction, and STBC. First, we generate multiple bitstreams based on wavelet trees along the spatial orientations to improve an error resilient capability so as to limit the error propagation in each bitstreams. The spatial-orientation trees in the wavelet domain are individually encoded using SPIHT. Second, we adopt R-S codes as FEC to combat transmission errors limited in each bitstreams over error-prone channels and detect residual errors so as to avoid error propagation in each bitstreams. Finally, we employ STBC to maximize the spatial diversity so as to improve SNR with no extra cost of bandwidth (data rate). We assume that channel state is perfectly estimated at the receiver end for STBC. The improved SNR thus alleviate the effect of multi-path fading that has been the main factor of high bit errors in mobile wireless network. We demonstrated that the integrated robust scheme can achieve excellent performance in terms of PSNR over Rayleigh flat channel as compared with system without the integrated diversity.

REFERENCES

[1] I. Moccagatta, S. Soudagar, J. Liang, and H. Chen, "Error-resilient coding in JPEG-2000 and MPEG-4," IEEE Journal on Selected Areas in Comm. vol. 18, no. 6, pp. 899-914, 2000.

[2] Y. Lee, K. Ong, and C. Lee, "Error-resilient image coding with smart-IDCT error concealment technique for wireless multimedia transmission," IEEE Trans. on CSVT, vol. 13, no. 2, pp. 176-181, 2003.

[3] Q. Chen and T. Fisher, "Image coding using robust quantization for noisy digital transmission," IEEE Trans. on Image Processing, vol. 7, no.4 , pp. 496-505, 1998.

[4] P. Sherwood and K. Zeger, "Progressive image coding for noisy channels," IEEE Signal Processing Letter, vol. 4, no. 7, pp. 189-191, 1997.

[5] S. M. Alamouti, "A simple transmit diversity scheme for wireless communications," IEEE J. Select. Areas Commun., vol. 16, pp. 1451-1458, Oct. 1998.

[6] V. Tarokh, H. Jafarkhani, and A. R. Calderbank, "Space-time block coding for wireless communications: Performance results," IEEE J. Select. Areas Commun., vol. 17, pp. 451-460, Mar. 1990.

[7] S. A. Martucci, I. Sodagar, T. Ching, and Y. Q. Zhang, "A zerotree wavelet video coder," IEEE Trans. on CSVT, vol. 7, pp. 109-118, 1997.

[8] A. Said and W. A. Pearlman, "A new fast, and efficient image codec based on set partitioning in hierarchical trees," IEEE Trans. on CSVT. 6, pp. 243-250, 1996.

[9] C. D. Creusere, "A new method of robust image compression based on the embedded zerotree wavelet algorithm," IEEE Trans. on Image Processing, vol. 6, pp. 1436-1442, 1997.

[10] V. Tarokh, N. Seshadri, and A. R. Calderbank, "Space-time codes for high data rate wireless communication: Performance criterion and code construction," IEEE Trans. on Information Theory, vol. 44, pp. 744-765, Mar. 1998.

[11] V. Tarokh, H. Jafarkhani, and A. R. Calderbank, "Space-time block codes from orthogonal designs," IEEE Trans. on Information Theory, vol. 45, pp. 1456-1467, July 1999.

(a) System without diversity (left) and 2×2 MIMO (right) at 12.5 [dB].

(b) System without diversity (left) and 2×2 MIMO (right) at 15 [dB].

(c) System without diversity (left) and 2×2 MIMO (right) at 17.5 [dB].

Figure 7: Reconstructed example images of no diversity system and 2×2 STBC MIMO system at various total power to the noise variance (12.5[dB], 15[dB], and 17.5 [dB])