AN UNEQUAL ERROR PROTECTION SCHEME FOR MULTIPLE INPUT MULTIPLE OUTPUT SYSTEMS

M. Farooq Sabir, Robert W. Heath and Alan C. Bovik

Dept. of Electrical and Comp. Engg., The University of Texas at Austin, Austin, TX, 78712-1084 USA
{mfsabir, rheath, bovik}@ece.utexas.edu

ABSTRACT

Rapid progress has been made in the use of spatial diversity for reliable communication over wireless channels. A large amount of work has been done in the field of unequal error protection and joint source-channel coding for reliable and efficient transmission of data over wireline and wireless channels. However, the use of unequal error protection in the temporal domain, combined with the advantages of multiple-input multiple-output communication systems has yet to be explored. In this paper an unequal error protection scheme based on the combined use of turbo codes and space-time codes for communication over wireless channels is proposed. This scheme assigns more coding gain and temporal diversity to important bits but assigns more spatial diversity and less coding gain to less important bits. Simulations illustrate a 25% *reduction in average transmission time and a* 15*dB improvement compared with no spatial diversity.*

1. INTRODUCTION

Over the last two decades, a large amount of work has been done in the field of joint source channel coding and unequal error protection for the transmission of data over wireline and wireless channels. The need for such schemes arises due to the conflicting requirement of obtaining high fidelity for image and video transmission with drastically limited (and fluctuating) channel bandwidth. If channel coding is performed in a way that exploits the inherent redundancy and structure in the data source, however, then high fidelity data can be reconstructed at the receiver even at high bit error rates (BER).

Practical approaches for joint source channel coding are often based on the notion of unequal error protection in which bits that are more important for source fidelity are protected (or encoded) differently than bits that are less essential to source fidelity. For example, [1] partitions a digital video into different substreams and applies different levels of error protection to each stream. Similarly, [2] proposes to partition an MPEG coded bitstream for wireless transmission, and then apply different levels of error protection on the different partitions. A different approach based on non-uniform constellations and convolutional codes is discussed in [3]. Various other joint-source channel coding techniques are discussed in [4–8].

Recently there has been significant interest in multiple-input multiple-output (MIMO) communication systems in which antenna arrays are used at both the transmitter and receiver to improve coverage, quality, and capacity (e.g., [9] or [10] and the references therein). MIMO systems offer an interesting tradeoff between capacity or data rate and diversity or reliability [11]. The benefits of MIMO communication to systems that feature unequal error protection, however, has yet to be exploited.

In this paper, we propose a scheme for providing unequal error protection both in the spatial domains (via space-time coding [12, 13]) and the time domain (via punctured convolutional codes). To vary the amount of spatial diversity, we use three different block codes. One is equivalent to BLAST or spatial multiplexing [9] [11], one is a variation of [13], and one is a hybrid of the two. For decoding simplicity we assume the use of a simple zero-forcing linear receiver for all three coding schemes. Selection diversity is used to extract diversity when symbols are repeated in the partial or full diversity case. To illustrate our scheme, we simulate a particular scheme in a Rayleigh fading matrix channel model with independent identically distributed Complex Gaussian coefficients using Embedded Foveation Image Coding (EFIC) [14]. Our approach reduces transmission time by 25% relative to the full diversity scenario with only 1dB loss in error probability performance.

This paper is organized as follows. Section 2 of this paper provides some background on turbo codes and MIMO systems. Then in Section 3 we discuss the system model and highlight our key assumptions. In Section 4 we describes our unequal error protection and unequal spatial diversity based scheme. Section 5 presents numerical and visual results while in Section 6 we present our conclusions.

2. BACKGROUND

2.1. Punctured Turbo Codes

Turbo codes [15,16] are one of the most commonly used error correction codes for communication over wireless channels. In a turbo encoder, encoding is performed by two ‘recursive systematic convolutional encoders’, connected in parallel and separated by a random interleaver. If bits are removed from the encoded bitstream to get a higher rate code then this process is known as puncturing. If puncturing is performed such that higher rate codes are embedded in the lower rate codes, then this process is called rate compatible puncturing. At the decoder side, zeros can be inserted at the punctured locations and either a maximum aposteriori algorithm (MAP) or a soft output viterbi algorithm (SOVA) can be used for decoding. The different rate codes can be used to protect the different portions of a bitstream to provide an unequal error protection scheme and then the same MAP or SOVA decoder can be used to decode the entire bitstream, after inserting zeros at the punctured locations.

2.2. Unequal Spatial Diversity

Spatial diversity in the form of multiple transmit and receive antennas can be used to transmit a bitstream in order to decrease the transmission errors. Maximum spatial diversity is provided by transmitting every bit using each antenna. However intelligent schemes can be devised to transmit certain most important bits using the maximum number of antennas and the least important bits using only one antenna. In this way, unequal spatial diversity can be provided to different parts of the bitstream. This decreases the bit error rate (BER) for the most important part of data while increasing the transmission time, and decreases the transmission time for the least important part of data, while increasing the BER.

3. SYSTEM MODEL

Consider a wireless communication system with 2 transmit antennas and 2 receive antennas. The transmitter consists of a source encoder followed by a concatenated space-time channel coder. The outer channel encoder consists of a rate $1/3$ turbo encoder. Different rate codes are derived from this turbo encoder by puncturing. The inner space-time code will be described later. Different source encoders can be used, however in our case we use Embedded Foveation Image Coding (EFIC) [14] based source encoder and decoder. EFIC is a scalable image compression technique, in which the bitstream is arranged such that the bits that contribute the most to the foveated visual distortion are encoded and transmitted first. The receiver uses an estimate of the channel to extract a soft estimate of the transmitted bit stream. This stream is then passed through a Soft Output Viterbi Algorithm (SOVA) based turbo decoder and then a source decoder. Note that at the receiver, the bitstream can be truncated and decoded any point to get different compression ratios. We tested this image specifically on EFIC, because in EFIC the bitstream is ordered according to the importance of data and hence it is easier to apply different rate codes to different parts of the bitstream.

To map the symbol streams with varying rates and qualities we assume the use of three different space-time block codes. Let s_0, s_1, s_2, s_3 be complex symbols that are to be transmitted. The mapping functions for the three proposed space-time block codes are given by

$$\mathbf{S} = \begin{bmatrix} s_0 & s_1 \\ s_2 & s_3 \end{bmatrix}, \begin{bmatrix} s_0 & s_1 \\ s_2 & s_0 \end{bmatrix}, \begin{bmatrix} s_0 & s_1 \\ s_1 & s_0 \end{bmatrix} \tag{1}$$

where each row corresponds to a transmission antenna and each column corresponds to a time slot. In 1, the first matrix corresponds to the case when we transmit 4 symbols in 2 time intervals i.e., spatial multiplexing [11] [9]. We refer to this as the no spatial diversity case since there is no redundancy across the transmit antennas for these symbols. The second matrix corresponds to the case when we transmit 3 symbols in 2 time intervals that will call partial spatial diversity. Note in this case that s_0 appears on two antennas while s_1 and s_2 do not. The third matrix corresponds to full spatial diversity, since we transmit 2 symbols on 2 transmit antennas and is a variation of [13]. We do not use the conjugate since we will use a suboptimal receiver that is identical for all three block codes.

Suppose that the bandwidth is much less than the coherence bandwidth of the channel, the antennas are spaced at a distance much greater than the coherence distance, and that there is a significant amount of interleaving in time. In this case we can assume that the channel is modeled by a matrix $\mathbf{H}$ whose entries are i.i.d. complex Gaussian with distribution $\mathcal{N}(0, 1/2)$ per dimension. We assume that the channel is constant over two symbol periods but varies independently in the next pair of symbol periods. This assumption can be realized in moderately fast fading channels with a suitable interleaver design. Concatenating two time periods together, we write the received signal as

$$\mathbf{R} = \begin{bmatrix} r_0 & r_1 \\ r_2 & r_3 \end{bmatrix} = \mathbf{HS} + \mathbf{N} \tag{2}$$

where each row of $\mathbf{R}$ corresponds to a receive antenna and each column represents a time sample. In the above equation, $\mathbf{H}$ is the channel matrix and $\mathbf{N}$ represents two i.i.d Gaussian noise row vectors.

$$\mathbf{H} = \begin{bmatrix} h_0 & h_1 \\ h_2 & h_3 \end{bmatrix}, \mathbf{N} = \begin{bmatrix} n_0 & n_1 \\ n_2 & n_3 \end{bmatrix}$$

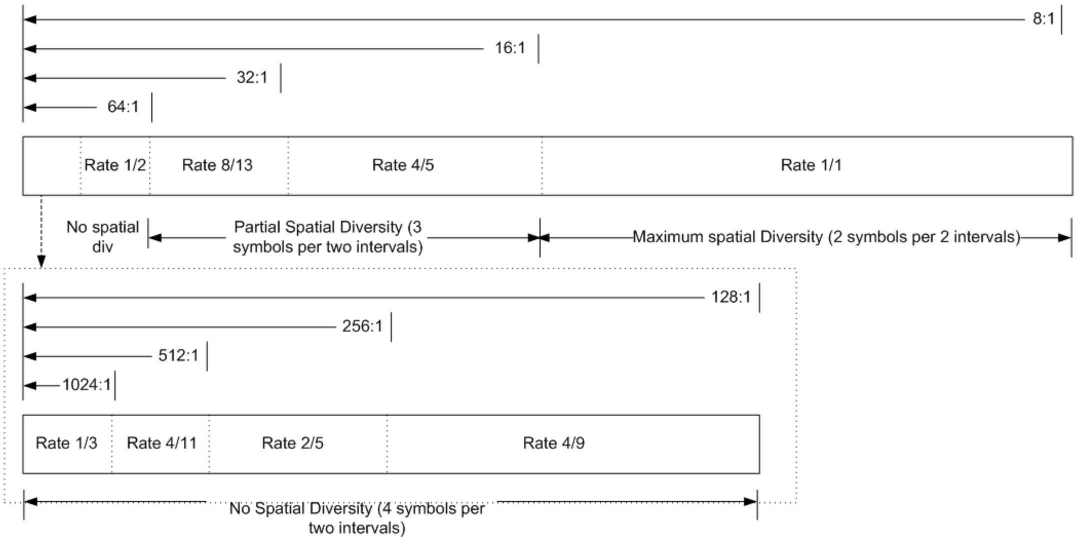

Fig. 1. EFIC bitstream with UEP in both time and spatial domains.

We assume the use of Binary Phase Shift Keying (BPSK) for modulation though the proposed method is readily extendable to higher order constellations.

At the receiver, to simplify the decoding process, we propose to use the zero-forcing receiver to remove the mixing caused by $\mathbf{H}$. In this case, the received symbol matrix is then multiplied with the pseudo-inverse $\mathbf{G}$ of the channel, given in the usual way by

$$\mathbf{G} \;=\; (\mathbf{H}^{*}\mathbf{H})^{-1}\mathbf{H}^{*} \tag{3}$$

and used to form

$$\widetilde{\mathbf{S}} \;=\; \mathbf{GR} \;=\; \mathbf{GHS} \;+\; \mathbf{GN} \;=\; \mathbf{S} \;+\; \mathbf{GN} \tag{4}$$

where * donates the Hermitian of a matrix.

After multiplying the received matrix with the channel pseudo-inverse, the first block (no spatial diversity) is directly passed to the SOVA decoder. For the cases of full or partial diversity, however, we first apply a selection procedure in which we select the symbol estimate corresponding to the transmit antenna with the best post-processing SNR (as determined by the norm of the rows of $\mathbf{G}$). For the full diversity case, the selector selects the bitstream with higher SNR in the case of third block for every two symbol intervals and then pass this selected group of two symbols to the SOVA decoder. For the partial diversity case, the selector selects the symbol with higher SNR, that was transmitted using spatial diversity (one out of every three bits) and passes this selected symbol along with the other two symbols that do not have any spatial diversity to the SOVA decoder.

The SNR is computed as given in [17] and is written

$$SNR_k = \frac{E_s}{MN_0[\mathbf{H}^{*}\mathbf{H}]^{-1}_{kk}} \tag{5}$$

where k corresponds to the k^{th} row of $\mathbf{G}$. Since E_s/N_0 and M (number of symbols simultaneously transmitted, i.e. 2) are the same, hence, the selection criteria [17] becomes

Select the symbol in k^{th} row of R if,

$$\frac{1}{[\mathbf{H}^{*}\mathbf{H}]^{-1}_{kk}} \geq \frac{1}{[\mathbf{H}^{*}\mathbf{H}]^{-1}_{ll}} \tag{6}$$

where k and l are two different rows of $\mathbf{G}$ (and $\mathbf{R}$). This selected symbol along with the two other symbols which do not have any spatial diversity are then passed to the SOVA decoder for decoding.

4. PROPOSED SPACE-TIME UEP FRAMEWORK

Consider the model illustrated in Fig. 1. The source encoded bitstream is first divided into 8 sub-blocks and each block is protected with a different rate turbo code, derived from the same rate $1/3$ mother code by puncturing. After turbo encoding, the bitstream is divided into 3 sub-blocks, and these sub-blocks are transmitted using different space-time codes as discussed in section 3. Full spatial diversity is provided to the part of the bitstream that is protected the least in the time domain. The part of the bitstream that is protected using intermediate rate channel codes is transmitted using partial spatial diversity. No spatial diversity is provided to the part of the bitstream that is protected the most in the time domain. Since we used 8 sub-blocks in time domain, therefore the bits within each of these new 3 sub-blocks are also unequally protected.

The intuition behind this “inverse” approach results from the ability of a code to obtain diversity in fast fading channels. With the spatial multiplexing block code we transmit

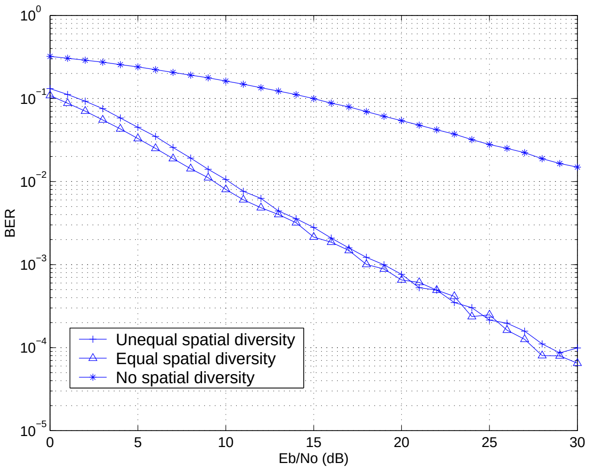

Fig. 2. BER vs SNR comparison for no spatial diversity, partial spatial diversity and full spatial diversity for EFIC compressed bitstream.

four symbols in two time periods thus we can afford to use a lower rate error control code. Since the channel is also varying in time, and since the turbo encoder uses a large interleaver, we will obtain both coding gain and diversity gain with this approach. We send the least protected bits on the low-rate space-time block code since the extra spatial diversity compensates for the loss of temporal diversity due to the puncturing of the code. The partial diversity case provides a mixture of both benefits again due to interleaving. Thus in our proposed system we tradeoff rate, diversity, and reliability by taking advantage of both diversity in the time and spatial domains.

This scheme of providing unequal error protection and unequal spatial diversity is show in Fig. 1 for the EFIC compressed bitstream. The different blocks in the bitstream correspond to the data with different visual importance, and hence different compression ratios. After channel decoding, the bitstream is passed to the source decoder.

5. SIMULATION RESULTS

To compute the performance of our proposed scheme, we performed a Monte Carlo simulation with 100 frames. We estimated the BER as a function of the SNR and have illustrated the result in Fig. 2. As can be seen from Fig. 2, the overall BER for the variable spatial diversity case remains within 1dB of that of the uniform spatial diversity case. Thus our approach does incur a substantial penalty in terms of error rate. By computing the overall rate of our code, however, we find that the overall transmission time is reduced by 25% for the unequal spatial diversity as compared to that of the uniform spatial diversity case for the EFIC bitstream. When compared to the no spatial diversity case, the un-equal spatial diversity scheme has a 15dB coding gain advantage and a 25% lower transmission time at SNR as low as 10^{-1} for the EFIC bitstream.

In order to visually illustrate the resulting reconstruction we transmitted the Zelda image over a Rayleigh fading channel at 22dB SNR. We randomly selected one of the reconstructed images and illustrate both the original Zelda image and the resulting reconstruction in Fig. 3. For comparison, the original image, along with the equal spatial diversity and no spatial diversity cases are also shown. It can be seen that the unequal error protection combined with unequal spatial diversity performs better in terms of visual image quality as compared to that of the equal spatial diversity and no spatial diversity and yet improves bandwidth efficiency.

6. CONCLUSION

We presented an unequal error protection scheme based on the combined use of turbo codes and unequal spatial diversity for MIMO systems. Results show that we can provide different levels of redundancy in both domains, providing higher level of protection to some data in one domain and lower protection in the other. In this way we can optimize the use of channel bandwidth to transmit high fidelity multimedia. This scheme performs better as compared to providing no spatial diversity, and also shows results that are comparable to maximum uniform spatial diversity (within 1dB coding gain).

We considered only selection diversity for the detection purpose. Even better results can be achieved if we consider other methods like maximum ratio combining and successive interference cancellation, etc. An interesting extension to this work can be to model this problem as a combined optimization of channel coding and spatial diversity. In this way, the encoder can assign optimized channel codes and space time codes for minimum bandwidth usage depending on the importance of data. This scheme can in turn be optimized even further if the transmitter has partial or full channel knowledge, which it can utilize to perform optimized channel and space-time coding. We are currently investigating this approach.

7. REFERENCES

[1] H. Gharavi and S. M. Alamouti, “Multipriority video transmission for third-generation wireless communication systems,” *Proceedings of the IEEE*, vol. 87, pp. 1751–1763, Oct. 1999.

[2] H. Gharavi and C. I. Richards, “Partitioning of mpeg coded video bitstreams for wireless transmission,” *IEEE Signal Processing Letters*, vol. 4, pp. 153–155, June 1997.

[3] A. R. Calderbank and N. Seshadri, “Multilevel codes for unequal error protection,” *IEEE Transactions on Information Theory*, vol. 39, pp. 1234–1248, July 1993.

(a) (b)

(c) (d)

Fig. 3. Transmission over a Rayleigh fading channel at 22dB SNR (a) Original Zelda image, (b) Decoded image with UEP and unequal spatial diversity (c) Decoded image with UEP and equal spatial diversity (d) Decoded image with UEP and no spatial diversity.

[4] P. Burlina and F. Alajaji, “An error resilient scheme for image transmission over noisy channels with memory,” *IEEE Transactions on Image Processing*, vol. 7, pp. 593–600, Apr. 1998.

[5] D.-F. Yuan, Z.-W. Li, and F. Zhang, “A new unequal error protection scheme for mobile hierarchical image transmission system using multilevel codes,” *IEEE Vehicular Technology Conference, VTC 2001 Spring, IEEE VTS 53rd*, vol. 3, pp. 2036–2040, 2001.

[6] J. Bakus and A. Khandani, “Combined source-channel coding using turbo-codes,” *Electronics Letters*, vol. 33, pp. 1613–1614, Sept. 1997.

[7] H.-X. Tie, A. Goldsmith, and M. Effros, “Joint design of fixed-rate source codes and UEP channel codes for fading channels,” *Conference Record of the Thirty-Second Asilomar Conference on Signals, Systems & Computers*, vol. 1, pp. 92–96, 1998.

[8] S. ZManji and N. Mandayam, “Variable rate channel coding and enhanced interleaving for image transmission using an outage criterion,” *IEEE Wireless Communications and Networking Conference*, vol. 1, pp. 344–348, 1999.

[9] G. J. Foschini, “Layered space-time architecture for wireless communication in a fading environment when using multiple antennas,” *Bell Labs Technical Journal*, vol. 1, no. 2, pp. 41–59, 1996.

[10] R. W. H. Jr., *Space-time Signaling in Multi-Antenna Systems*. PhD thesis, Stanford University, November 2001.

[11] R. W. H. Jr. and A. Paulraj, “Switching between spatial multiplexing and transmit diversity based on constellation distance,” in *Proc. of Allerton Conf. on Comm. Cont. and Comp.*, Oct. 2000.

[12] V. Tarokh, N. Seshadri, and A. R. Calderbank, “Space-time codes for high data rate wireless communication: Performance criteria and code construction,” *IEEE Trans. Information Theory*, vol. 44, pp. 744–764, Mar. 1998.

[13] S. M. Alamouti, “A simple transmit diversity technique for wireless communications,” *IEEE J. Select. Areas Commun.*, vol. 16, pp. 1451–1458, Oct. 1998.

[14] Z. Wang and A. C. Bovik, “Embedded Foveation Image Coding,” *IEEE Transactions on Image Processing*, vol. 10, pp. 1397–1410, Oct. 2001.

[15] C. Berrou and A. Glavieux, “Near optimum error correcting coding and decoding: turbo-codes,” *IEEE Transactions on Communications*, vol. 44, pp. 1261 –1271, Oct. 1996.

[16] B. Vucetic and J. Yuan, “Turbo codes.” Kluwer Academic Publishers, 2000.

[17] R. W. Heath, S. Sandhu, and A. Paulraj, “Antenna selection for spatial multiplexing systems with linear receivers,” *IEEE Communications Letters*, vol. 5, pp. 142–144, Apr. 2001.