A Flexible Space-Time Coding System with Unequal Error Protection

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Abstract—Most multimedia source coders exhibit unequal bit error sensitivity. Efficient transmission system design should therefore incorporate the use of matching unequal error protection (UEP). In this paper, we present and evaluate a flexible space-time coding system with unequal error protection. Multiple transmit and receive antennas and bit-interleaved coded modulation techniques are used combined with rate compatible punctured convolutional codes. A near optimum iterative receiver is employed with a multiple-in multiple-out inverse mapper and a MAP decoder as component decoders. We illustrate how the UEP system gain can be achieved either as a power or bandwidth gain compared to the equal error protection system (EEP) for the identical source and equal overall quality for both the UEP and EEP systems. An example with two/three transmit and two receive antennas using 8PSK modulation is given for the block fading channel.

I. INTRODUCTION

Recently, Space-Time Coding have emerged as a technology for power and bandwidth efficient radio links. This is achieved by means of multiple transmit and receive antennas with matching signal design and signal processing. Applications to 4th generation cellular and high speed wireless local area networks are possible. A flexible space-time coding system is described and evaluated in [1].

The bit stream from most real world source coding algorithms for speech, audio, images and video exhibits unequal bit error sensitivity for different bits. Several modifications can be introduced to source coding, in order to enhance their resilience to transmission errors [2]. Due to the error-prone wireless channels, automatic repeat request (ARQ) or forward error correction (FEC) codes are required to reduce the error rate on wireless channels. In order to minimize the amount of overhead added by FEC codes, many digital communication and broadcasting systems are using unequal error protection (UEP) to match the transmission schemes to the digital source, see e.g. [3] for speech, [4] for audio and [2] for video telephony application.

In [5] and [6], video data is partitioned into high-priority (HP) and low-priority (LP) layers according to the importance of the data. Then, based on the feedback of sub-channel partitioning results, the transmitter assigns HP and LP video data to the corresponding high-quality and low-quality sub-channels, respectively. In [5], power control is employed to provide the same signal-to-noise ratio (SNR) to the same group, while [6] exploits the features of space-time block coded orthogonal frequency division multiplexing (STBC-OFDM) systems. In these schemes, the channel profile needs to be fed back from the receiver to the transmitter. The design and performance of a low bit-rate video telephony service for 3G systems is presented in [2] based on the concatenated channel coding with convolutional inner coding and Reed-Solomon (RS) outer coding.

The precise needs and the best coding schemes depend on the particular source as well as channel properties. It is therefore important to obtain a flexible method of channel codes where it is easy to design different protection levels. The rate compatible punctured convolutional (RCPC) Codes is such a class of codes [7]. These codes have been used for UEP with QPSK modulation [4][7] and with bit-interleaved coded modulation (BICM) and higher order signal constellations [8]. In this paper, we propose and evaluate a UEP scheme in space-time BICM (ST-BICM) systems with iterative decoding (ID). By applying iterative algorithm, the performance of BICM system is further improved over both fading and additive white Gaussian noise (AWGN) channels because of the increased harmonic mean of the minimum squared Euclidean distance and free Euclidean distance (FED) [9][10]. As in the previous cases, the outcome depends not only on the source but also on the channel. However, with a rich class of systems, good matches can be found in a flexible framework.

For wideband ST-BICM, OFDM is used in the transmitter and receiver structures [1] to handle frequency selective fading. For flat fading channels, single carrier modems are used. Block fading and fast fading type of channels affect the performance.

It is easy to see the gains with UEP over equal error
Section V. the paper is terminated by a discussion and conclusions in IV, the simulation results and evaluation is provided. Finally performance for ST-BICM system in Section III. In Section II. S YSTEM MODEL AND STRUCTURE

In this section, we consider the ST-BICM system with \( N_t \) transmit and \( N_r \) receive antennas. \( N_t \) is typically larger than or equal to \( N_r \). The modem constellations used are \( M \)-PSK or \( M \)-QAM with \( M \) constellation points. Figure 1 shows a transmitter for an ST-BICM system with unequal error protection. We build on the ST-BICM system in [1], which is an equal error protection system. In this case the binary convolutional coder is fixed. It may be a punctured code, but the code is one and the same for all source bits.

In this paper we modify the structure in [1] by replacing the fixed convolutional coder with a number of compatible punctured codes [4] with different rates. For illustrational reasons, we describe a simple example of Figure 3 where a rate \( R = 1/3 \) convolutional code with memory \( m = 4 \) is shown. Information bits from all classes are first encoded by the same mother convolutional coder. Then, the encoded bits of Class I, Class II and Class III are punctured periodically with period \( p=4 \) according to the puncturing table \( P(1), P(2) \) and \( P(3) \), respectively. A zero in the puncturing table \( P(l) \) means that the code symbol is not to be transmitted. The index \( l \) defines class identifier. The protection levels and code rates are chosen to match a number of bit error sensitivity classes for a given source.

A frame with bits from different classes is organized as in [3][4]. The bitstreams of the source coder based on the transform predictive coding (TPC) paradigm have a natural hierarchy in error sensitivity that can be exploited in a UEP approach [4]. In the case of G.723.1 audio codec, the most sensitive bits cannot tolerate a bit error rate (BER) \( > 5 \times 10^{-5} \), while the remaining bits can tolerate a BER as high as \( 10^{-3} \).

In order to evaluate the performance of the proposed UEP scheme for a variety of configurations, let us assume that each frame consists of three classes of information bits with different bit error sensitivity. we consider two source coders that require different UEP schemes: UEP1 where the most sensitive bits of Class I can not tolerate a BER \( > 5 \times 10^{-5} \), while the remaining Class II and III, consisting of less sensitive bits each, can tolerate a BER as high as \( 10^{-3} \) and \( 5 \times 10^{-2} \), respectively, and UEP2 where Class I, II and III require about \( 5 \times 10^{-5} \), \( 5 \times 10^{-4} \) and \( 5 \times 10^{-3} \) BER performance, respectively. Frame synchronization is established between the transmitter and receiver. The frame length can be coupled to the interleaver size in the BICM, but this is not necessary.

In what follows, we consider zero-mean complex valued baseband signal models and multi-input multi-output (MIMO) OFDM channel model. Let us define the \( N_t \)-dimensional complex transmitted vector signal \( x_k = [x_{k1}^T \cdots x_{kN_t}^T] \) where \( (\cdot)^T \) denotes the transpose, the \( N_t \)-dimensional complex received vector signal \( y_k = [y_{k1}^T \cdots y_{kN_r}^T] \). Then the received signal at the \( k \)th subcarrier can be written as [1]

\[ y_k = H_k x_k + n_k \]  

(1)
and

\[ H_k = \begin{bmatrix} h_{k1}^{1,1} & \cdots & h_{kN_t}^{1,1} \\ \vdots & \ddots & \vdots \\ h_{k1}^{N_r} & \cdots & h_{kN_t}^{N_r} \end{bmatrix}, \quad n_k = \begin{bmatrix} n_k^1 \\ \vdots \\ n_k^{N_r} \end{bmatrix} \]

where \( h_{ki}^{ij} \) denotes the channel coefficients from the \( i \)th transmit antenna to the \( j \)th receive antenna and additive noise terms of \( n_k \) are independent and identically-distributed complex zero mean Gaussian variables with variance \( N_0/2 \) per dimension.

Figure 2 shows the ST-BICM UEP receiver structure. The puncturing is added to the trellis in the MAP decoder in [1]. The most efficient receiver structure with an iterative decoder is shown in [1], where the turbo principle is used. Simpler receivers with lower complexity are also possible both for the EEP case [1] and for the UEP case. For example using the Viterbi decoder without receiver iterations is possible.

Let \( b_k^n \) be the bit that is mapped into the \( n \)th bit position \( (n = 1, 2, \ldots, N_t M) \) in the input symbol vector \( x_k \). At the receiver in Figure 2, the demapper extracts the extrinsic log-likelihood ratio (LLR) values of the estimated symbol sequence by the MAP rule as

\[
L_e(b_k^n) = \log \frac{P(b_k^n = +1|y_k, H_k)}{P(b_k^n = -1|y_k, H_k)} = \log \frac{\sum_{x_k \in S_k^+} p(x_k, y_k, H_k)}{\sum_{x_k \in S_k^-} p(x_k, y_k, H_k)} \tag{2}
\]

where \( S_k^0, d = \pm 1 \), denotes the signal subset of all symbol vectors with a +1 or -1 value of bit \( b_k^n \), respectively.

The joint probability density function in (2) is related to

\[
p(x_k, y_k, H_k) \propto \exp \left( -\frac{1}{N_o} \| y_k - H_k x_k \|^2 \right) + \frac{1}{2} b_k^T L_k \]

where \( b_k \) and \( L_k \) are column vectors comprised of \( b_k^n \) and the extrinsic LLR values from the MAP decoder.

For ST-BICM systems with iterative decoding, the overall performance is affected by the mapping pattern. In [11], general BICM-ID mappings are divided into two groups where each group exhibits a distinctive bit error rate (BER) curve. In BER curves, one mapping group reaches an error floor at a low SNR, while the other has a lower error floor at a higher SNR. All mapping groups for ST-BICM/BICM-ID with 8PSK and the optimal selection for each mapping group over independent fading channels was described in [11]. What is interesting in [11] is that their proposed mapping pattern exhibits the steeper slope for high SNRs than the conventional Gray mapping. Therefore, we can make use of their mapping to improve the BER performance of Class II and III. In the simulation section, we use the mapping in [11] to compare with a Gray mapping.

III. PAIRWISE ERROR PROBABILITY

For equal error protection ST-BICM system under the exact feedback assumption and assuming the block fading narrow band flat fading channel, the average pairwise error probability (PEP) is shown in [12] [13]. Denoting \( x \) and \( \hat{x} \) as the correct sequence and the erroneous sequence, respectively, the pairwise error probability (PEP) at high signal-to-noise ratios is bounded by

\[
P(x \rightarrow \hat{x}) \leq \left( \prod_{i=1}^{N_t} \frac{E_s}{4N_o} d_{E}^i(x_i, \hat{x}_i) \right)^{-N_r} \tag{3}
\]

where we define \( d_{E}^i(x_i, \hat{x}_i) \) as the sum of the squared Euclidean distances computed on the subsequence transmitted over the \( i \)th transmit antennas and \( E_s \) is the symbol energy. Expression (3) is given for the dominant error event. It is clear from the above approximate bound that the maximum diversity order for the EEP ST-BICM systems in block fading channels is equal to \( N_t N_r \). Note that this will only be achieved if the Hamming distances associated with all \( N_t \) transmit antennas are nonzero [12]. The same expression as in (3) also applies for UEP systems where the diversity order and the Euclidean distance components vary with the protection level. Thus we get a different expression for the portion corresponding to the different punctured code. For error events with that covers two of the RCPC codes we get performance in between the two codes.

TABLE I

<table>
<thead>
<tr>
<th>Protection type</th>
<th>Class I Rate</th>
<th>Class II Rate</th>
<th>Class III Rate</th>
<th>Information Bits</th>
<th>Coded Bits</th>
</tr>
</thead>
<tbody>
<tr>
<td>UEP</td>
<td>1/3</td>
<td>1/3</td>
<td>1/3</td>
<td>360</td>
<td>1080</td>
</tr>
<tr>
<td>UEP-BW</td>
<td>1/3</td>
<td>1/2</td>
<td>2/3</td>
<td>360</td>
<td>780</td>
</tr>
<tr>
<td>UEP-PO</td>
<td>1/4</td>
<td>1/3</td>
<td>1/2</td>
<td>360</td>
<td>1080</td>
</tr>
</tbody>
</table>

TABLE II

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<thead>
<tr>
<th>Protection type</th>
<th>Class I Rate</th>
<th>Class II Rate</th>
<th>Class III Rate</th>
<th>Information Bits</th>
<th>Coded Bits</th>
</tr>
</thead>
<tbody>
<tr>
<td>EEP</td>
<td>1/3</td>
<td>1/3</td>
<td>1/3</td>
<td>512</td>
<td>1536</td>
</tr>
<tr>
<td>UEP-PO</td>
<td>1/4</td>
<td>1/3</td>
<td>1/2</td>
<td>512</td>
<td>1536</td>
</tr>
</tbody>
</table>

TABLE III

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<tr>
<th>Protection type</th>
<th>Class I Rate</th>
<th>Class II Rate</th>
<th>Class III Rate</th>
<th>Information Bits</th>
<th>Coded Bits</th>
</tr>
</thead>
<tbody>
<tr>
<td>UEP</td>
<td>1/3</td>
<td>1/3</td>
<td>1/3</td>
<td>768</td>
<td>2304</td>
</tr>
<tr>
<td>UEP-PO</td>
<td>1/4</td>
<td>1/3</td>
<td>1/2</td>
<td>774</td>
<td>2304</td>
</tr>
</tbody>
</table>
IV. SIMULATION RESULTS AND EVALUATION

In this section, we present simulation results for a flexible ST-BICM system with UEP. Binary convolutional codes with polynomials $(23,35,27)$ and $(23,35,27,33)$ in octal notation are used for the mother code of rate $1/3$ and $1/4$, respectively, in the simulations. Puncturing patterns for the RCPC codes with memory $m = 4$ is depicted in Figure 3. The decoder employs the maximum a posteriori (MAP) algorithm and the iterative decoding procedure is similar to [1] except the puncturing.

Figure 5 shows BER of the 2 by 2 ST-BICM system over flat fading channels. Each class code rate for the three level UEP and EEP schemes is listed in Table I, where the UEP-BW and UEP-PO configurations correspond to UEP for bandwidth gain and power gain, respectively. Note that we use one single channel coder with a single MAP decoder based on the puncturing rule. For comparison reason, we also include the simulation results for EEP case. In Figure 5, the simulation results for UEP-PO demonstrate about 2 dB power gain over the EEP schemes at no extra cost in bandwidth. Alternatively, for UEP-BW, about 28% saving in bandwidth is obtained compared to EEP without loss of quality as the same protection level for the most sensitive bits is guaranteed.

In what follows, we design the ST-BICM OFDM systems over frequency selective channels to provide two different UEP cases described in Section II. A 5-tap multipath channel with exponentially decaying delay profile is used throughout the simulations.

First, we demonstrate a ST-BICM UEP system where we employ a Gray mapping shown in Figure 4 to realize UEP1 scheme. Table II shows code rates for the UEP and EEP schemes. Figures 6 and 7 show the simulation results for the 2 by 2 system with iteration 1 and 3, respectively. We can see that the UEP scheme provides about 2 dB power gain over the EEP schemes without any violation against the class bit sensitivities in UEP1. Also, Figure 6 and 7 demonstrate that the performance gain is more than 2 dB with three iterations. We can employ another mapping pattern, namely $G_{3,0}$, proposed in [11]. As stated earlier, the mapping $G_{3,0}$ shown in Figure 4 is more beneficial to the lower-level classes. We apply this mapping to realize UEP2 scheme where the variance of the protection levels is small. It is shown in Figure 8 that, with the UEP employing $G_{3,0}$, about 1.5 dB power gain can be obtained at the expense of a higher BER on the less sensitive bits, but still lower the error protection levels in UEP2.

Figure 9 presents the performance comparison between EEP and UEP with Gay mapping in the 3 by 2 system. Simulation configurations about the 3 by 2 ST-BICM OFDM system are shown in Table III. As observed in the previous 2 by 2 systems with Gay mapping, the simulation results for UEP-PO demonstrates about 2 dB power gain over the EEP schemes. These simulation results confirm that the proposed UEP scheme can provide consistent protection level by matching the FEC to the need regardless of the number of transmit and receive antennas and the channel characteristics.

Finally, Figure 10 shows that the proposed structure can provide widely different error protection levels between classes of short information blocks. Note that the bits close to the beginning and all-zero tail of the frame and to the transition to the next class with a lower code rate get better protection.

V. DISCUSSION AND CONCLUSIONS

We have demonstrated a flexible ST-BICM UEP system by using a rate compatible puncturing scheme in flat fading or frequency selective fading. These systems work well for the important case with a larger number of transmit than receive antennas. Also, we illustrate how the UEP system gain can be achieved either as a power or bandwidth gain compared to the EEP system for the identical source and equal overall quality for both the UEP and EEP systems.

As mentioned in [13], we have some open issues relating to ST-BICM, especially the choice of constellation mapper and receiver complexity for high data rate constellation cases. It is straightforward to generalize the systems in this paper to adaptive multi-rate ST-BICM for both the EEP and UEP cases.
Fig. 7. Comparison of EEP and UEP with Gray mapping in the 2 by 2 system over 5-tap exponentially decayed fading channel (iteration=3)

Fig. 8. Comparison of EEP and UEP with $G_{3,0}$ mapping in the 2 by 2 system over 5-tap exponentially decayed fading channel (iteration=3)

Fig. 9. Comparison of EEP and UEP with Gray mapping in the 3 by 2 system over 5-tap exponentially decayed fading channel (iteration=3)

Fig. 10. BER in a data frame with three-level UEP

REFERENCES


