MIMO-OFDM 시스템을 위한 효율적인 UEP 전송기법 제안

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An Efficient UEP Transmission Scheme for MIMO-OFDM Systems

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요 약

소스 코딩을 통해 얻어지는 대다수의 멀티미디어 데이터 정보는 여러 등급의 다른 비트에러민감도를 가지고 있다. 그러므로 효율적인 시스템 구현을 위해서는 데이터 고유의 비트에러민감도에 따라 서로 다른 수준의 에러 방지를 제공해야 한다. 이 논문에서는 다중안테나 (multiple-in multiple-out : MIMO) 기반의 OFDM시스템에서 효과적인 멀티미디어 정보를 전송하기 위한 차등 에러 방지 기법(Unequal error protection : UEP)을 제안한다. 차등의 에러 방지를 제공하는 시공간 코딩 기법을 설명하고 그 성능을 평가한다. MIMO 기법과 BICM (Bit-interleaved coded modulations) 기술은 보통 RCPC (Rate compatible punctured convolutional codes) 기법과 연계되어 구동된다. 이때 다중안테나 채널 이퀄라이저와 채널코딩 사이에 터보디코딩 기법을 적용하여 최상의 성능을 얻을 수 있는데 기존의 시스템에서는 동일한 에러방지기법(Equal Error Protection : EEP)을 사용하고 있다. 이 논문에서는 이런 시스템 구조에서 보통 사용되는 동일 에러 방지 기법(EEP)와 비교하여 차등 에러방지 기법(UEP)를 사용함으로써 얻을 수 있는 이득을 사용되는 전송파워와 채널밴드 측면에서 설명한다. 특히 제안된 알고리즘을 둘 또는 세 개의 전송 안테나와 두 개의 수신안테나를 갖는 다중안테나 시스템에 적용하고 8PSK 신호를 이용하여 플랫 페이딩 채널에서 성능을 평가하였다.

Key Words : Multi-input multi-output (MIMO) systems, Orthogonal Frequency-Division Multiplexing (OFDM), Unequal error protection (UEP), Bit-interleaved coded modulations (BICM), and Rate compatible punctured convolutional codes (RCPC)

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.

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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. And 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. [5] further employs power control 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 protection (EEP). In the EEP system, the error protection has to be designed for the most sensitive bits, because these will determine the performance. The overall result is that bits then are wasted for the protection of the least sensitive bits, since they in the EEP system have the same protection level as the most sensitive bits. On the other hand, the UEP system matches the protection level to the system requirement. The punctured bits in the punctured codes represent savings in bit rate (or bandwidth) without loss of quality. For this to work in practice, the UEP codes have to be simple and flexible to design and apply. This is the case with the RCPC type of systems[3][4]. Alternatively, the gain with UEP over EEP can be converted to a power gain. In this case we compare the two systems at equal bandwidth. For the UEP scheme, a more powerful code and improved protection level can be used for the most sensitive bits. This paper is organized as follows. The system model and structure is presented in Section II. Based on the pair-wise error probability analysis, we reviewed the performance for ST-BICM system in Section III. In Section IV, the simulation results and evaluation is provided. Finally the paper is terminated by a discussion and conclusions in Section V.

Ⅱ. System 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 constellation used are M-PSK or M-QAM with M constellation points. Figure 1 shows a transmitter for a ST-BICM 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.

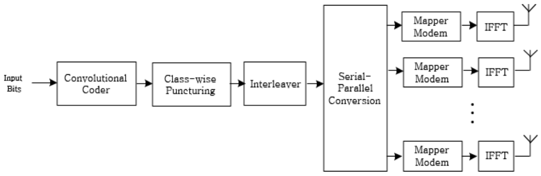

Figure 1. Transmitter structure for ST-BICM-OFDM with UEP.

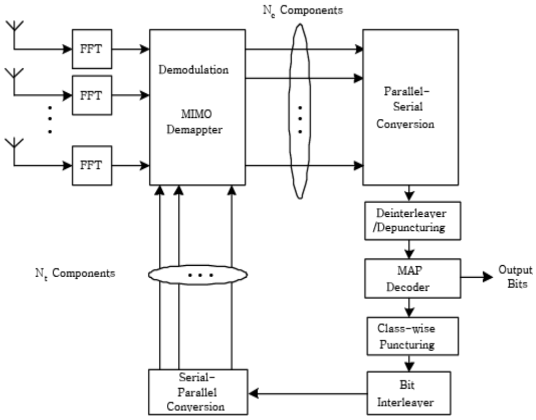

Figure 2. Receiver structure for ST-BICM-OFDM with UEP.

A frame with bits from different classes is organized as in [3] and [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 BER $>5\times10^{-5}$, 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 $>5\times10^{-5}$, while the remaining Class II and III, consisting of less sensitive bits each, can tolerate a BER as high as 10^{-3} and 5×10^{-2}, respectively, and UEP2 where Class I, II and III require about 5×10^{-5}, 5×10^{-4}

and 5×10^{-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 $\boldsymbol{x_k}=[x_k^1\cdots x_k^{N_t}]^T$ where $(\cdot)^T$ denotes the transpose, the N_r-dimensional complex received vector signal $\boldsymbol{y_k}=[y_k^1\cdots y_k^{N_r}]^T$. Then the received signal at the kth subcarrier can be written as[1]

$$\boldsymbol{y_k}=\boldsymbol{H_k}\boldsymbol{x_k}+\boldsymbol{n_k} \tag{1}$$

and

$$\boldsymbol{H_k}=\begin{bmatrix} h_k^{1,1} & \cdots & h_k^{N_t,1} \\ \vdots & \ddots & \vdots \\ h_k^{1,N_r} & \cdots & h_k^{N_t,N_r}\end{bmatrix},\quad \boldsymbol{n_k}=\begin{bmatrix} n_k^1 \\ \vdots \\ n_k^{N_r}\end{bmatrix}$$

where $h_k^{i,j}$ denotes the channel coefficients from the ith transmit antenna to the jth receive antenna and additive noise terms of $\boldsymbol{n_k}$ are independent and identically-distributed complex zero mean Gaussian variables with variance $N_o/2$ 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 nth bit position $(n=1,2,\cdots,N_tM)$ in the input symbol vector $\boldsymbol{x_k}$. 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

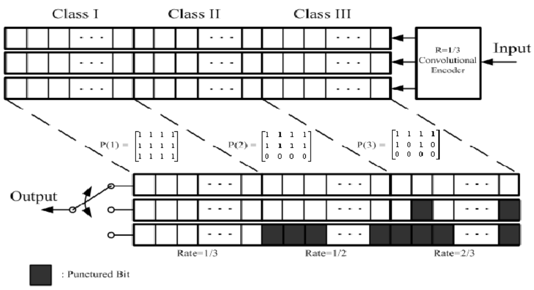

Figure 3. Example of RCPC of a mother code with rate = $1/3$ and three puncturing table $P(1)$, $P(2)$ and $P(3)$ with rates $1/3$, $1/2$ and $2/3$.

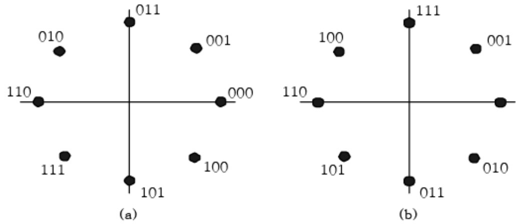

Figure 4. (a) Gray mapping (b) $G_{3.0}$ mapping

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

where $S_d^n, d=\pm1$, 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

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

where $\boldsymbol{b_k}$ and $\boldsymbol{L_k}$ are column vectors comprised of b_k^n and the extrinsic LLR values from the MAP decoder, respectively.

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 Gay 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. Pair-wise 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 $\boldsymbol{x}$ and $\hat{\boldsymbol{x}}$ as the correct sequence and the erroneous sequence, respectively, the pairwise error probability(PEP) at high signal-to-noise ratios is bounded by

$$P(\boldsymbol{x}\rightarrow\hat{\boldsymbol{x}}) \leq \left(\prod_{i=1}^{N_t}\frac{E_s}{4N_o}d_E^i(\boldsymbol{x},\hat{\boldsymbol{x}})\right)^{-N_r} \qquad (3)$$

where we define $d_E^i(\boldsymbol{x},\hat{\boldsymbol{x}})$ as the sum of the squared Euclidean distances computed on the subsequence transmitted over the ith 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_tN_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.

Ⅳ. Simulation Results and Evaluation

In this section, we present simulation results for a flexible ST-BICM system with UEP. A binary convolutional code with polynomials (23,35) in octal notation is used for 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

Table Ⅰ. Three-level UEP and EEP (8PSK, N_t=2, N_r=2, Flat-fading)

Protection type	Class Ⅰ Rate	Class Ⅱ Rate	Class Ⅱ Rate	Information bits	Coded Bits
EEP	1/3	1/3	1/3	360	1080
UEP-BW	1/3	1/2	2/3	360	780
UEP-PO	1/4	1/3	1/2	360	1080

Table Ⅱ. Three-level UEP and EEP (8PSK, N_t=2, N_r=2, 256 Subcarriers)

Protection type	Class Ⅰ Rate	Class Ⅱ Rate	Class Ⅱ Rate	Information bits	Coded Bits
EEP	1/3	1/3	1/3	512	1536
UEP-PO	1/4	1/3	1/2	512	1536

Table Ⅲ. Three-level UEP and EEP (8PSK, N_t=3, N_r=2, 256 Subcarriers)

Protection type	Class Ⅰ Rate	Class Ⅱ Rate	Class Ⅱ Rate	Information bits	Coded Bits
EEP	1/3	1/3	1/3	768	2304
UEP-PO	1/4	1/3	1/2	774	2304

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 multi path 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.

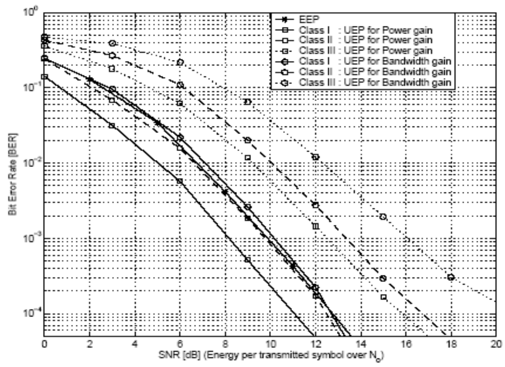

Figure 5. Comparison of EEP and UEP with Gray mapping in the 2 by 2 system over flat fading channel (iteration=3)

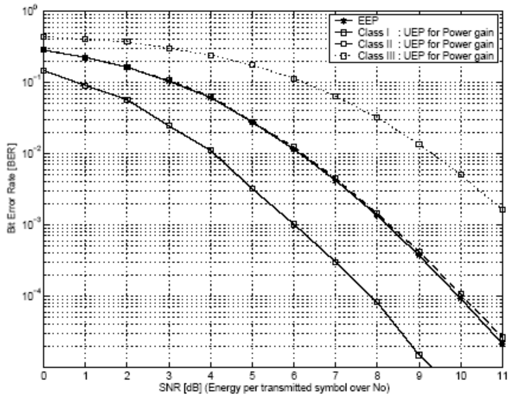

Figure 6. Comparison of EEP and UEP with Gray mapping in the 2 by 2 system over 5-tap exponentially decayed fading channel (iteration=1)

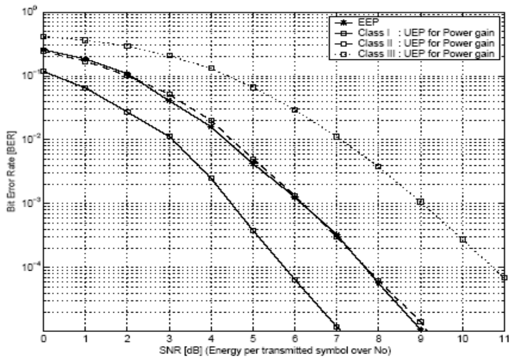

Figure 7. Comparison of EEP and UEP with Gray mapping in the 2 by 2 system over 5-tap exponentially decayed fading channel (iteration=3)

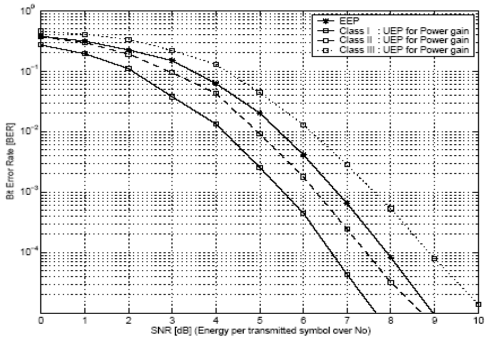

Figure 8. Comparison of EEP and UEP with $G_{3.0}$ mapping in the 2 by 2 system over 5-tap exponentially decayed fading channel (iteration=3)

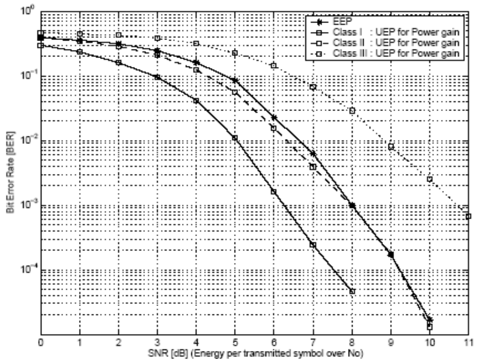

Figure 9. Comparison of EEP and UEP with Gray mapping in the 3 by 2 system over 5-tap exponentially decayed fading channel (iteration=3)

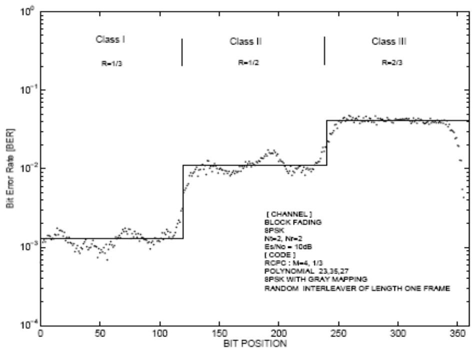

Figure 10. BER in a data frame with three-level UEP

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. Conclusions

We have demonstrated a flexible ST-BICM UEP system by using 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.

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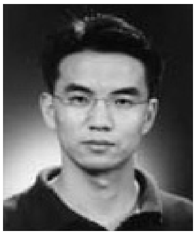

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