Turbo Unequal Error Protection Codes with Multiple Protection Levels

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Abstract

Most existing Turbo unequal error protection (UEP) codes provide two error protection levels at the cost of extending the block size of the codeword or increasing the computational complexity. This paper proposes two novel Turbo UEP coding schemes, which provide multiple error protection levels for information bits, according to their different sensitivities to the channel noise. By permuting the information bits and designing the puncturing scheme, multiple error protection levels can be achieved using one encoder without increasing the computational complexity. In addition, the coding rate of the proposed Turbo UEP schemes can be chosen from 1/3 to 1/2. Experimental results show that the information bits with a high protection level resist noise more effectively than those with a low protection level. The proposed UEP schemes provide better capability of error protection for the entire information, compared with the Turbo equal error protection (EEP) schemes and the existing Turbo UEP schemes.

Keywords: Bit Error Rate (BER), rate-compatible punctured convolutional (RCPC) codes, turbo codes, unequal error protection (UEP)

1 Introduction

Error correction coding is a popular measure that is used to resist channel noise in communication systems. There are many error correction codes, such as linear block code, convolutional code, and Turbo code. These codes have good error correction capabilities, however, they provide equal error correction capabilities to all the information bits even though information has different sensitivities to noise when transmitted in a communication channel. This diversity results from the different kinds of source information and the different bits that comprise a piece of information. Therefore, information bits should be protected to greater or lesser extents, depending on their sensitivities to the channel noise.

In order to provide variable error protection capabilities for different bits of information, several kinds of error correction coding schemes usually are used in a communication system [13, 20, 26]. In these systems, the important information is usually coded by some codes that have high error correction capabilities and low coding rates, while the less important information is coded by some other codes that have low error correction capabilities and high coding rates. Thus, information bits are provided different levels of error protection according to their different sensitivities to the noise.

However, using several coding schemes increases the complexity of the encoder and causes time delays. To provide unequal error correction capabilities by one encoder, Unequal Error Protection (UEP) codes were proposed. The UEP capabilities were achieved by improving the conventional error correction codes. By changing the structures of their coding space, the probability of the errors occurring in the important bits becomes less than the probability of their occurring in the less important bits after decoding. That is to say, the UEP codes usually don't decrease the overall number of errors, but control the locations at which the errors occur. By this approach, the UEP codes provide unequal error protections for information by a one-shot coding process and decrease the effect of channel noise on the entire information.

The UEP code was first proposed by Masnick and Wolf in 1967, and a linear block UEP code was proposed by them [17]. After that, many researchers made significant contributions in this field. Gils proposed a cyclic UEP code and proved its capability of providing unequal error protection [9]. For the transmission of source messages that contain packets of different importance over lossy packet erasure links, Vukobratovic and Stankovic provided a performance analysis method of random linear UEP codes [8]. In order to achieve better error correction performance, some non-linear channel coding schemes were considered to achieve UEP capabilities. Hagenauer proposed a punctured convolutional coding scheme to obtain flexible coding rates to meet different error protection needs of the source information or different channel situations [10]. After that, the UEP coding schemes based on the rate-compatible punctured convolutional (RCPC) mechanism were studied extensively [21, 31].

In recent years, Turbo codes have been attracting more and more attention because of their perfect error correction capabilities. Turbo codes have been studied extensively and have been applied in a number of communication systems [3, 4, 7]. The conventional Turbo code provides equal error protection for every information bit. Since a Turbo encoder is composed of two recursive systematic convolutional (RSC) encoders, the UEP schemes for convolutional codes can be easily used in Turbo codes. Based on a rate-compatible puncturing mechanism, Barbulescu *et al.* proposed a Turbo UEP code with two error protection levels [2]. This scheme provided UEP capabilities for the information bits in a coding block, but it decreased the coding rate, compared to the conventional Turbo code. To overcome this problem, some special modulations or interleaving schemes must be used. Rowitch and Milstein proposed a hybrid forward-error correction/automatic repeat-request (FEC/ARQ) system which was based on Hagenauer's RCPC mechanism [22]. In addition, they proposed the criteria for designing the puncturing patterns in [23]. Jung and Plechinger proposed a design method for the rate-compatible punctured Turbo codes for mobile radio applications and illustrated its viability by simulation [12]. By partitioning the coding block of the Turbo code into many sub-blocks according to their importance, Caire and Biglieri achieved multiple UEP capability in a coding block [5]. Zhou improved Caire's scheme in [30]. However, for both schemes, the outputs of the two recursive systematic convolutional encoders were punctured independently, which decreases the average Bit Error Rate (BER) of the entire coding block. In addition, Aydinlik and Salehi derived the performance bounds of the Turbo UEP codes, which can be used to predict the codes' performance [1].

The UEP schemes can be used in image transmission to achieve better quality. Thomos et al. proposed an optimal UEP scheme for the compressed images, which employed Turbo codes and Reed-Solomon codes [25]. Lakhdar et al. proposed a UEP scheme, for which the puncturing operation was controlled by a periodic matrix [14]. They applied this Turbo UEP code in JPEG image transmission and achieved better image quality. Mao et al. proposed a Turbo UEP coding scheme and applied it for the transmission of images compressed by Discrete Cosine Transform (DCT) [16]. However, all of these schemes provide only two protection levels. Zhang et al. pointed out that each information bit in a Turbo block can possess a different protection level [28]. They proposed a Turbo code that provides descending protection capabilities for the information bits according to their locations in a block, and used this UEP scheme to JPEG image transmission to achieve better quality.

The Turbo UEP code decreases the BERs of the important bits at the cost of increasing the BERs of the unimportant bits, while the BER of the entire coding block varies very little. Therefore, the UEP capabilities should depend on the characteristics of the source information. That is to say, for an UEP coding scheme, the different sensitivities of the information bits to the channel noise should decide the number of the error protection levels, the length of each level, and the error correction capability of each level. But, until now, most Turbo UEP codes can provide only two protection levels, i.e., high and low error protection levels, and the error correction capability of each level is fixed and cannot be designed arbitrarily.

In this paper, we propose two novel Turbo UEP schemes. The main contributions of the proposed schemes are:

1) The proposed schemes provide multiple error protection levels by a one-shot coding process.

2) Most existing schemes obtain UEP capability at the cost of decreasing the coding rate. However, the proposed Turbo UEP codes have the same coding rate with the normal Turbo code.

The rest of the paper is organized as follows. Section 2 gives preliminary information about the proposed schemes. Section 3 shows the structures and algorithms of the proposed Turbo UEP codes. In Section 4, the performances of the proposed schemes are analyzed by simulations. Our conclusions are presented in Section 5.

2 Preliminaries

In this section, the coding theory of the conventional Turbo code, which is the foundation of the proposed Turbo UEP schemes, is briefly analyzed.

A Turbo encoder is composed of an interleaver, two RSC encoders, and a puncturing mechanism, as shown in Figure 1.

Assume that the generator matrix of both RSC encoders is $G(D) = [1 \quad \mathrm{g}_2(D)/\mathrm{g}_1(D)]$, where $\mathrm{g}_1(D) = \mathrm{g}_{10}+\mathrm{g}_{11}D+\cdots+\mathrm{g}_{1,K-1}D^{K-1}$, $\mathrm{g}_2(D) = \mathrm{g}_{20}+\mathrm{g}_{21}D+\cdots+\mathrm{g}_{2,K-1}D^{K-1}$, and K is the constraint length. Parameter $\mathrm{g}_{i,j} (i = 1, 2$ and $j = 0, 1, \cdots, K-1)$ is a binary number that is pre-determined. In addition, we assume that the range of the input message of the encoder is $\{0, 1\}$, and d_k is the k^{th} information bit, where $k = 1, 2, \cdots, L$ and L is the size of the coding block. Then, for the input bit d_k, there are three output bits of the Turbo encoder, which

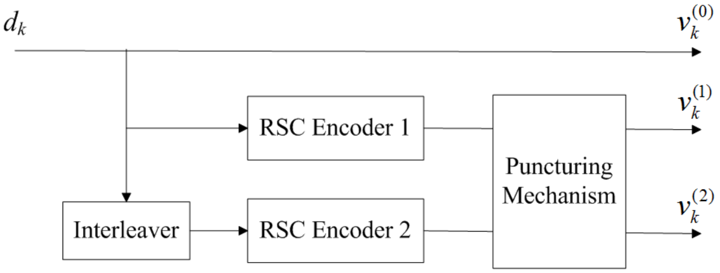

Figure 1: Framework of turbo encoder

are $v_k^{(0)}$, $v_k^{(1)}$, and $v_k^{(2)}$, as shown in Figure 1. The output bit $v_k^{(0)}$ is exactly the information bit d_k, i.e.,

$$v_k^{(0)} = d_k. \tag{1}$$

The second output $v_k^{(1)}$ is the parity-check bit of d_k computed by RSC Encoder 1, which is

$$v_k^{(1)} = \sum_{i=0}^{K-1} \mathrm{g}_{2i} a_{k-i} \bmod 2, \tag{2}$$

where

$$\begin{aligned} a_r &= d_r + \sum_{i=1}^{K-1} \mathrm{g}_{1i} a_{r-i} \bmod 2, \text{ and} \\ r &= k, k-1, \cdots, k-(K-1). \end{aligned} \tag{3}$$

To resist burst noise in the communication channel, the original bit sequence is randomly permuted by an interleaver, as shown in Figure 1. Then, the permuted bit sequence is sent to RSC Encoder 2, which has the same structure as RSC Encoder 1. By this approach, the third output $v_k^{(2)}$, which is also computed by Equations (2) and (3), is obtained [4].

Therefore, for each coding block, the output V of the Turbo encoder is composed of the original information bits and the parity-check bits, as shown in the following:

$$\begin{aligned} V = \{ & v_1^{(0)}, v_1^{(1)}, v_1^{(2)}, v_2^{(0)}, v_2^{(1)}, v_2^{(2)}, v_3^{(0)}, v_3^{(1)}, \\ & v_3^{(2)}, v_4^{(0)}, v_4^{(1)}, v_4^{(2)}, \cdots, v_L^{(0)}, v_L^{(1)}, v_L^{(2)}\}. \end{aligned} \tag{4}$$

The coding rate (CR) of Equation (4) is 1/3. In order to enhance the coding rate, a puncturing mechanism can be used. Compared to parity-check bits, the information bits convey more information about the original message, thus, the puncturing operation only deletes parity-check bits. For the conventional Turbo encoder, the deleted bits are usually located periodically. For example, the puncturing algorithm may delete the bits on the even locations in $v_k^{(1)}$ and the bits on the odd locations in $v_k^{(2)}$. By this means, half of the parity-check bits are deleted, and the output $V_{\text{punctured}}$ with a size of $2L$ is obtained as follows:

$$\begin{aligned} V_{\text{punctured}} = \{ & v_1^{(0)}, v_1^{(1)}, v_2^{(0)}, v_2^{(2)}, v_3^{(0)}, v_3^{(1)}, \\ & v_4^{(0)}, v_4^{(2)}, \cdots, v_L^{(0)}, v_L^{(2)}\}. \end{aligned} \tag{5}$$

Following that, the encoded sequence is first modulated to binary antipodal digits then is transmitted through a noisy channel. The sequence received by the recipient is denoted as:

$$\begin{aligned} R = \{ & r_1^{(0)}, r_1^{(1)}, r_1^{(2)}, r_2^{(0)}, r_2^{(1)}, r_2^{(2)}, r_3^{(0)}, r_3^{(1)}, \\ & r_3^{(2)}, r_4^{(0)}, r_4^{(1)}, r_4^{(2)}, \cdots, r_L^{(0)}, r_L^{(1)}, r_L^{(2)}\}. \end{aligned} \tag{6}$$

In the receiver side, the decoder first uses a de-puncturing mechanism to classify $r_k^{(0)}$, $r_k^{(1)}$, and $r_k^{(2)}$ in R. The de-puncturing mechanism is the inverse operation of the puncturing mechanism of the encoder. After that, $r_k^{(0)}$ and $r_k^{(1)}$ are sent to Decoder 1, and $r_k^{(0)}$ and $r_k^{(2)}$ are sent to Decoder 2. Then, an iterative decoding process is conducted between the two decoders. The whole decoding process is shown as Figure 2.

In the decoding process, the two decoders implement a soft decision using the log-likelihood ratio of the received stream R. Assuming that there is a mapping for every transmitted bit $v_k^{(j)} (j = 0, 1, 2) : 0 \to -1$ and $1 \to +1$, then, for the Additive White Gaussian Noise (AWGN) channel, the log-likelihood ratio of the information bit d_k under the condition of $r_k^{(0)}$ is:

$$\begin{aligned} \lambda(d_k | r_k^{(0)}) &= \ln \frac{P(d_k = +1 | r_k^{(0)})}{P(d_k = -1 | r_k^{(0)})} \\ &= 4 \frac{E_s}{N_0} r_k^{(0)} + \ln \frac{P(d_k = +1)}{P(d_k = -1)} \\ &= \lambda_c r_k^{(0)} + \lambda_a(d_k), \end{aligned} \tag{7}$$

where E_s/N_0 is the Signal-to-Noise Ratio (SNR) of the channel, $\lambda_c = 4(E_s/N_0)$ is defined as the channel reliability factor, and $\lambda_a(d_k)$ is the *a priori* λ value of d_k.

For the parity-check bit $v_k^{(j)} (j = 1, 2)$, the log-likelihood ratio λ under the condition of $r_k^{(j)}$ is:

$$\lambda(v_k^{(j)} | r_k^{(j)}) = \lambda_c r_k^{(j)} + \lambda_a(v_k^{(j)}), \quad j = 1, 2. \tag{8}$$

When decoding, each decoder has three inputs, i.e., the soft outputs from the channel, which are $\lambda_c r_k^{(0)}$ and $\lambda_c r_k^{(1)}$(or $\lambda_c r_k^{(2)}$), and the *a priori* λ value $\lambda_a^{(1)}(d_k)$ (or $\lambda_a^{(2)}(d_k)$). For each decoder, the *a priori* λ value is the extrinsic information of another decoder, i.e., $\lambda_a^{(1)}(d_k) =$

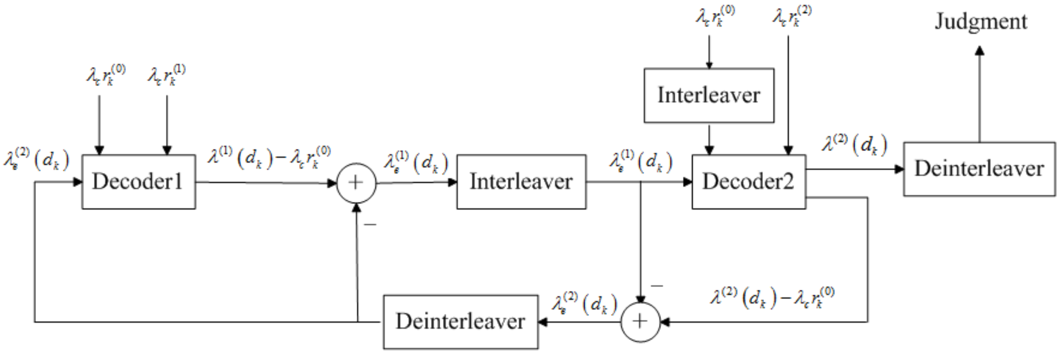

Figure 2: Framework of turbo decoder

$\lambda_e^{(2)}(d_k)$ and $\lambda_a^{(2)}(d_k) = \lambda_e^{(1)}(d_k)$. Each decoder has two outputs. The first one is $\lambda^{(1)}(d_k)$ (or $\lambda^{(2)}(d_k)$), which is the *a posteriori* λ value of d_k under the condition of the received bits and the *a priori* λ values. The second output is the extrinsic information of d_k, $\lambda_e^{(1)}(d_k)$(or $\lambda_e^{(2)}(d_k)$), which will be transferred to another decoder as the *a priori* λ value. Therefore, the two decoders implement an iterative, soft-decision algorithm. Each of iterations makes the judgment more reliable. The Turbo decoder outputs the final judgment after several iterations.

3 Proposed Turbo UEP Schemes with Multiple Protection Levels

The puncturing mechanism of the conventional Turbo code deletes half of the parity-check bits and enhances the coding rate from 1/3 to 1/2. This coding scheme provides Equal Error Protection (EEP) capabilities for all the information bits, which is defined as Turbo EEP code. In this section, two novel Turbo UEP schemes with multiple protection levels are proposed. The first UEP scheme has a flexible coding rate, and the second scheme has a fixed coding rate, which is 1/2.

3.1 Turbo UEP Code with Flexible Coding Rate

In digital communication, each bit for transmission usually has different importance for the transmitting contents. For example, the higher bits of 8-bits pixel value for an image are more important than the lower bits with respect to image representation. As a result, if the higher bits are damaged due to the channel noise, it will cause more serious influence on the transmitting contents than the condition that the lower bits are damaged. Therefore, in order to provide better protection for the bits with higher importance, we proposed a novel Turbo UEP coding scheme that provides different error correction capabilities to the information bits based on their importance to the transmitting contents.

Assuming that the block size of the Turbo UEP code is L and there are N protection levels in a block, of which protection capabilities decrease from the first level to the last level. Each protection level consists of $L_i(i = 1, 2, \cdots, N)$ information bits, thus, $L = L_1+L_2+\cdots+L_N$. Every information bit has two parity-check bits in a Turbo EEP coding scheme without puncturing. In our proposed UEP scheme, the number of the parity-check bits in each protection level is controlled in order to provide unequal protection level. That is to say, the higher the protection level is, the more information bits that have two parity-check bits there will be. We use the puncturing controller, P_{flexible}, to define this characteristic.

$$P_{\text{flexible}} = [p_1\ p_2\ \cdots\ p_N], \tag{9}$$

where $p_i(i = 1, 2, \cdots, N)$ is the percent of the information bits that have two parity-check bits in the i^{th} protection level, and $p_i \in [0, 1]$. That is to say, in the i^{th} protection level, there are $L_i \cdot p_i$ information bits with two parity-check bits, and the rest of the information bits in this level have only one parity-check bit. The value of $p_i(i = 1, 2, \cdots, N)$ depends on the sensitivity of the information bits in the i^{th} protection level to the channel noise. In addition, all of the information bits that have two parity-check bits should be chosen randomly in order to keep the error correction capability of the entire coding block at an acceptable level. The puncturing mechanism of the proposed Turbo UEP code is shown in Figure 3. In this figure, the shadowed blocks indicate the parity-check bits that are deleted by the puncturing mechanism. Figure 3 shows that there are more information bits that have two parity-check bits in the high protection level, and there are more information bits that have only one parity-check bit in the low protection level.

The coding procedures of our proposed Turbo UEP code with multiple protection levels and a flexible coding rate are listed below:

1) Permute the information bits in a coding block, i.e., put all the bits that belong to the same protection level together and array all the protection levels from high to low.

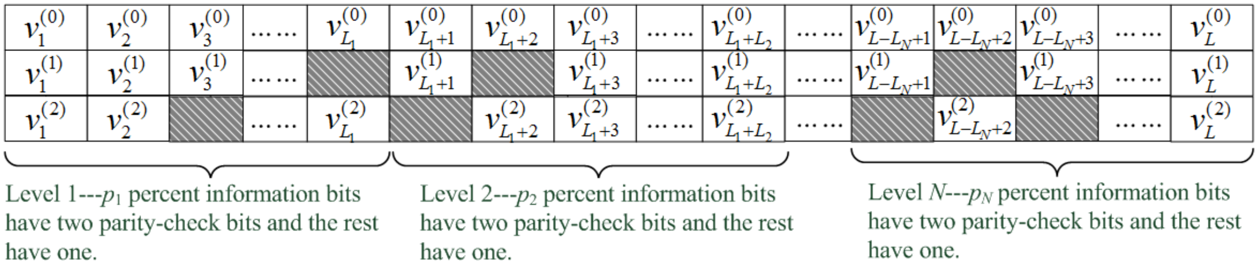

Figure 3: Puncturing mechanism of the turbo UEP code with multiple protection levels and a flexible coding rate

2) Determine the value of the puncturing controller, P_{flexible}, according to the different sensitivities to channel noise of the protection levels.

3) Design the puncturing mechanism for the Turbo encoder, according to P_{flexible}. For the i^{th} protection level, choose $L_i \cdot p_i$ information bits randomly, and reserve the two parity-check bits for them. The rest of the information bits in this protection level have only one parity-check bit. For the information bit $d_k(k = 1, 2, \cdots, L)$, if there should be only one parity-check bit and k is odd, $v_k^{(1)}$ is reserved for it; if k is even, $v_k^{(2)}$ is reserved.

4) Encode the rearranged information bits by (1) - (3) and get $v_k^{(0)}$, $v_k^{(1)}$, and $v_k^{(2)}$.

5) Puncture $v_k^{(0)}$, $v_k^{(1)}$, and $v_k^{(2)}$ by the proposed puncturing mechanism in Step 3. Transform the punctured outputs into a bit sequence and transmit it through the communication channel.

In the receiver side, the decoder uses the same puncturing algorithm to classify $r_k^{(0)}$, $r_k^{(1)}$, and $r_k^{(2)}$ in the received bit sequence, sends them to the decoders as shown in Figure 2, and starts an iterative decoding process. By this approach, the unequal error protection capabilities are achieved.

The coding rate of each protection level in the proposed Turbo UEP scheme is different, which depends on the value of p_i. The coding rate, CR_{flexible}, of the entire Turbo UEP code is:

$$CR_{\text{flexible}} = \frac{L}{\sum\limits_{i=1}^{N}(L_i + L_i + L_i \cdot p_i)} = \frac{L}{\sum\limits_{i=1}^{N} L_i(2 + P_i)}. \qquad (10)$$

The information bits that correspond to higher importance levels are assigned with two parity-check bits, while the information bits that correspond to lower importance levels are assigned with only one parity-check bits. Therefore, the value of CR_{flexible} depends on the puncturing controller P_{flexible}, and $1/3 \leq CR_{\text{flexible}} \leq 1/2$. When CR_{flexible} is equal to $1/3$, all information bits are assigned with two parity-check bits, which means that there is no puncturing operation and the protection capability is equal to the Turbo EEP code without puncturing. When CR_{flexible} is $1/2$, all information bits are assigned with only one parity-check bit, which leads to a Turbo EEP code with a coding rate of $1/2$.

An example is shown in the following. Assuming that the original data are decimal numbers ranging from 0 to 255, then, each number can be denoted as an 8-bit byte. It is clear that the highest bit in a byte is the most important and most sensitive to channel noise, and every bit in a byte has a different sensitivity to channel noise. Therefore, the proposed Turbo UEP code partitions a coding block into eight protection levels. All the highest bits of the 8-bit bytes are provided the highest error protection, all the second-highest bits are provided the second-highest error protection, and so on. The puncturing controller, $P_{\text{flexible},1}$, in this scheme is:

$$P_{\text{flexible},1} = \begin{bmatrix} 1 & \frac{1}{2} & \frac{1}{2^2} & \frac{1}{2^3} & \frac{1}{2^4} & \frac{1}{2^5} & \frac{1}{2^6} & \frac{1}{2^7} \end{bmatrix}. \qquad (11)$$

Puncturing controller $P_{\text{flexible},1}$ means that all the information bits in the first protection level have two parity-check bits, half of the information bits in the second protection level have two parity-check bits, and so on. Therefore, the coding rate of the Turbo UEP code with puncturing controller $P_{\text{flexible},1}$ is

$$\begin{aligned} CR_{\text{flexible},1} &= \frac{L}{\sum\limits_{i=1}^{8} \frac{L}{8}\left(2 + \frac{1}{2^{i-1}}\right)} \\ &= \frac{8}{16 + \left(1 + \frac{1}{2} + \frac{1}{2^2} + \cdots + \frac{1}{2^5} + \frac{1}{2^6} + \frac{1}{2^7}\right)} \\ &\approx 0.44. \end{aligned} \qquad (12)$$

3.2 Turbo UEP Code with Fixed Coding Rate

The Turbo UEP scheme proposed in Section 3.1 has a flexible coding rate. In order to achieve a fixed coding rate for the Turbo UEP code with multiple protection levels, another puncturing mechanism is proposed in this section. In this scheme, some bits in the high protection levels have two parity-check bits, while some bits in the low protection levels do not have a parity-check bit.

The puncturing controller, P_{fixed}, for the Turbo UEP code with a fixed coding rate can be denoted as:

$$P_{\text{fixed}} = [p_1 \; p_2 \; \cdots \; p_N], \tag{13}$$

where $p_i \in [-1, 1]$ and $i = 1, 2, \cdots N$. For the i^{th} protection level, if p_i is positive, there should be $L_i \cdot p_i$ information bits that have two parity-check bits; if p_i is negative, there should be $L_i \cdot |p_i|$ information bits that do not have a parity-check bit, where $|x|$ denotes the absolute value of x. In order to make the coding rate 1/2, the following requirement should be satisfied:

$$\sum_{i=1}^{N} L_i p_i = 0, \;\; i = 1, 2, \cdots, N. \tag{14}$$

The value of $p_i (i = 1, 2, \cdots, N)$ in Equation (13) depends on the sensitivity of the information bits in the i^{th} protection level to channel noise. Both the bits that have two parity-check bits and the bits that do not have a parity-check bit should be chosen randomly. The puncturing mechanism of the Turbo UEP code with multiple protection levels and a fixed coding rate is shown in Figure 4.

The coding procedures of the Turbo UEP code with a fixed coding rate are listed below:

1) Permute the information bits in a coding block. Put all the bits that belong to the same protection level together, and array all the protection levels from high to low.

2) Determine the value of the puncturing controller, P_{fixed}, according to the sensitivities of the protection levels to channel noise.

3) Design the puncturing mechanism for the encoder, according to P_{fixed}. For the i^{th} protection level, if p_i is positive, choose $L_i \cdot p_i$ information bits randomly and reserve their two parity-check bits; if p_i is negative, choose $L_i \cdot |p_i|$ information bits randomly and delete both of their parity-check bits. The rest of the information bits in this protection level have only one parity-check bit. For the information bit $d_k (k = 1, 2, \cdots, L)$, if there is only one parity-check bit and k is odd, $v_k^{(1)}$ is reserved; if k is even, $v_k^{(2)}$ is reserved.

4) Encode the rearranged information bits by (1) - (3) and get $v_k^{(0)}$, $v_k^{(1)}$, and $v_k^{(2)}$.

5) Puncture $v_k^{(0)}$, $v_k^{(1)}$, and $v_k^{(2)}$ by the proposed puncturing mechanism in Step 3. Transform the punctured outputs into a bit sequence and transmit it through the communication channel.

An example is shown as follows. Assuming that the original data are decimal numbers and every number is denoted as an 8-bit byte, the information bits in a coding block are partitioned into eight levels. All the highest bits of the 8-bit bytes are arrayed in the first level, all the second-highest bits are arrayed in the second level, and so on. To provide higher protection for the important bits and to keep the coding rate of the entire block as 1/2, the puncturing controller can be designed as follows:

$$P_{\text{fixed},1} = [0.3 \; 0.15 \; 0 \; 0 \; -0.1 \; -0.1 \; -0.1 \; -0.15]. \tag{15}$$

In this case, there are five protection levels in the UEP scheme and the coding rate is 1/2. The protection levels are designed as:

Level 1. The highest protection level. It consists of the highest bits of all the 8-bit bytes in a coding block. Among these highest bits, 30% of the information bits, which are chosen randomly, have two parity-check bits, and the rest of the information bits have only one parity-check bit each.

Level 2. The second-highest protection level. It consists of the second-highest bits of all the bytes in a block. Fifteen percent of the bits, which are chosen randomly, have two parity-check bits, and the rest of the bits have only one parity-check bit each.

Level 3. The third protection level. It consists of all the third and fourth bits of the 8-bit bytes, and all of the information bits in this part have only one parity-check bit.

Level 4. The fourth protection level. This is the second-lowest protection level, and it consists of all the fifth to the seventh bits of the bytes. Ten percent of the information bits in this protection level are chosen randomly, and they do not have a parity-check bit; the rest of the information bits have one parity-check bit each.

Level 5. The fifth protection level. This is the lowest protection level, and it consists of the lowest bits of all the bytes in a coding block. Fifteen percent of the information bits in this level are chosen randomly, and they have no parity-check bit; the rest of the information bits have one parity-check bit each.

Note that there are many reasonable schemes of the puncturing controller. Generally speaking, the number of the parity-check bits reserved in a protection level should be consistent with the importance of the information bits in this level. On the other hand, if too many information bits have no parity-check bit, the error correction performance of the entire coding block will be decreased. A large number of experiments show that the absolute value of $p_i (i = 1, 2, \cdots, N)$ in Equation (13) should not be larger than 50%. The value of P_{fixed} should be a trade-off between the UEP effect and the error correction performance of the entire coding block.

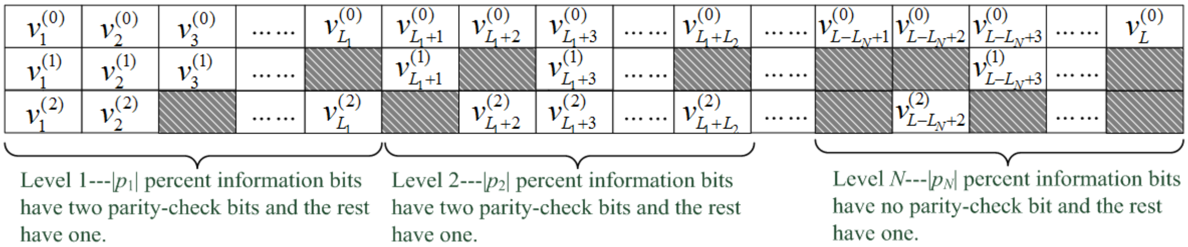

Figure 4: Puncturing mechanism of the turbo UEP code with multiple protection levels and a fixed coding rate

3.3 Evaluation Method of the Turbo UEP Code

The advantage of Turbo UEP code is that it provides unequal error correction capabilities for the information bits, according to their different sensitivities to channel noise. Therefore, the protection effect for the entire information is better than that of the Turbo EEP codes. In order to measure the different error correction capabilities for the information bits, the BER of each protection level should be measured and analyzed.

In order to measure the protection effect for the entire information, the standard deviation between the original data and the decoded data is used in this paper. Assuming that $X = [x_1, x_2, \cdots, x_Q]$ is the original information sequence in decimal form, $Y = [y_1, y_2, \cdots, y_Q]$is the decoded sequence in decimal form, and the lengths of sequences X and Y are both Q, the standard deviation, SD, between X and Y is:

$$SD = \left\{ \frac{\sum_{i=1}^{Q} [|x_i - y_i| - |\overline{X - Y}|]^2}{Q} \right\}^{\frac{1}{2}}, \tag{16}$$

where $|x_i - y_i|$ is the absolute value of $x_i - y_i$, and $|\overline{X - Y}|$ is the mean value of the absolute value of the difference between X and Y.

4 Experimental Results

In this section, the error correction performances of the proposed Turbo UEP codes are analyzed by simulation. All of the experiments were conducted in Matlab on a PC with 3.40 GHz Intel Core i7 CPU, 8GB main memory and Windows 7 OS. In the experiments, the transmission channel was the AWGN channel with Binary Phase Shift Keying (BPSK) modulation, and the input data were numbers ranging from 0 to 255. The parameters of Turbo code are shown in Table 1.

Table 1: Parameters of coding

Item	Value
Generate Matrix	$g_1(D) = 1 + D + D^2$ and $g_2(D) = 1 + D^2$
Decoding Algorithm	Log-MAP
Iteration Number	5
Block Length	802 bits
Quantity of the Protection Levels	8
Length of Each Protection Level	100 bits

In the experiments, the 800 information bits in a coding block (excepting the two tail bits) were partitioned into eight protection levels, which are represented as PL_1 to PL_8 from the highest level to the lowest level. Each protection level consists of 100 information bits. Since each original number can be denoted as an 8-bit byte, in our experiments, all the highest bits in a coding block were provided the highest protection level (PL_1), all the second-highest bits were provided the second-highest protection level (PL_2), and so on. For comparison, the following two Turbo UEP schemes were also analyzed:

- Turbo UEP scheme proposed by Z. D. Zhou [30]. In this scheme, the outputs of each RSC encoder are punctured by an independent puncturing matrix, which reserves all of the information bits and randomly punctures the parity-check bits according to the coding rate of each protection level.
- Turbo UEP scheme proposed by A. M. Lakhdar [14]. In this scheme, the outputs of the RSC encoders are punctured by a periodic puncturing matrix. In each period, all of the information bits are arrayed from high protection level to low protection level. For all of the information bits, 1) the information bits are reserved, and 2) the outputs of the second RSC encoder are alternatively punctured. The outputs of the first RSC encoder are punctured according to the protection level of the information bit. If the bit is highly protected, the first parity-check bit is reserved; if the bit is lowly protected, the first parity-check bit is alternatively punctured or completed punctured, according to the required coding rate.

In the following, the error protection performance of the proposed UEP Scheme 1 is first simulated. In the experiments, the SNR of the AWGN channel was 1.0 dB.

The experimental results are shown in Table 2. From the table, we see that the BER of the information bits with a high protection level is lower than that with a low protection level. This is because that there are more parity-check bits in this part. For comparison, Zhou's Turbo UEP scheme and a Turbo EEP scheme, which also have a coding rate of 0.44, are simulated. In Zhou's scheme, the parity-check bits of each RSC encoder are randomly punctured, keeping the coding rate of each protection level equal to the number indicated by Equation (11). In order to construct a Turbo EEP code with a coding rate of 0.44, some information bits are randomly chosen in the entire coding block and are reserved two parity-check bits, and the rest of the information bits have one parity-check bit. By this means, the coding rate of the Turbo EEP code can be controlled arbitrarily. From Table 2, we see that, although the average BER of the proposed UEP scheme is higher than that of the EEP scheme, which is due to the controlled puncturing mechanism of the UEP scheme, the standard deviation of the UEP scheme is lower than that of the EEP scheme. This means that the protection effect of the proposed UEP Scheme 1 is better than that of the EEP scheme with the same coding rate. For Zhou's Turbo UEP scheme, since the outputs of each RSC encoder are punctured independently, there are a quantity of information bits that have no parity-check bits, which leads to a highest BER and a highest standard deviation among the three schemes, as shown in Table 2.

The second experiment simulated a Turbo UEP scheme with a flexible coding rate and less protection levels. The puncturing controller of the proposed UEP Scheme 2 is:

$$P_{\text{flexible},2} = [1\ 0\ 0\ 0\ 0\ 0\ 0\ 0]. \tag{17}$$

From Equation (17), we see that there are only two different protection levels in this UEP scheme, i.e., all the highest bits are provided a high protection level, and all remaining bits are provided a low protection level. The coding rate, $CR_{\text{flexible},2}$, of this scheme is:

$$CR_{\text{flexible},2} = \frac{L}{\frac{L}{8}\cdot 3 + \frac{L}{8}\cdot 2\cdot 7} = \frac{8}{17} \approx 0.47. \tag{18}$$

The experimental results of the UEP Scheme 2 are shown in Table 2. From the table, we see that the BER of level PL_1 is lower than that of levels PL_2 to PL_8, and the last seven protection levels have approximately the same BER values. For the UEP scheme in [30], two independent puncturing matrices are generated, which reserves all of the parity-check bits for the high protection information bits and randomly punctures half of the parity-check bits of the low protection bits. For the UEP scheme in [14], since there is only one high protection bit in a period, the puncture matrix is:

$$P_{L1} = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 0 & 1 & 0 & 1 & 0 & 1 \\ 1 & 0 & 1 & 0 & 1 & 0 & 1 & 0 \end{bmatrix}.$$

This puncturing matrix provides two protection levels for the eight information bits in a byte and repeats the UEP with a period of eight, and the coding rate is 0.47. Table 2 shows that although the average BER of the proposed Turbo UEP Scheme 2 is not the best one, the standard deviation of the proposed scheme is the lowest. This means that the proposed scheme provides the best protection for the entire information.

The third experiment simulated the protection effects of the proposed UEP schemes with a fixed coding rate, which is 1/2. The puncturing controller of Scheme 3 is shown as Equation (15). Therefore, there are five protection levels in this scheme. The experimental results are shown in Table 2. We can see that the higher the protection level is, the lower its BER becomes.

The puncturing controller of the proposed UEP Scheme 4 is:

$$P_{\text{fixed},2} = [1\ 0\ 0\ 0\ 0\ 0\ 0\ \ {-1}]. \tag{19}$$

There are three protection levels in this scheme. All the highest bits are provided high protection, all the lowest bits are provided low protection, and the second through the seventh bits are provided middle error protection level. For comparison, the following three coding schemes are simulated: 1) a Turbo EEP code with a coding rate of 0.5 (EEP Scheme 3); 2) Zhou's UEP scheme [30], which reserves the two parity-check bits for the high protection bits, deletes all of the parity-check bits for the low protection bits, and randomly punctures half of the parity-check bits for the middle protection bits; and 3) Lakhdar's UEP scheme [14], which uses a puncturing matrix as follows:

$$P_{L2} = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 0 & 1 & 0 & 1 & 0 & 0 \\ 1 & 0 & 1 & 0 & 1 & 0 & 1 & 0 \end{bmatrix}.$$

The coding rates of the five schemes are both 1/2. Table 2 shows that the lowest standard deviation is achieved by the proposed UEP Scheme 4.

From the above experiments, we see that the average BER of the entire information of our proposed UEP scheme is increased, compared to the Turbo EEP codes. This is because the puncturing controller of the UEP scheme lowers the chaos of the received bit stream, thereby reducing the decoding performances. But the standard deviation of the proposed UEP schemes was lower than those of the EEP schemes and the existing UEP schemes with the same coding rate. This means that the proposed UEP schemes have the best protection effects for the entire information.

Figures 5 through 7 show the comparisons of the standard deviation between the proposed Turbo UEP schemes and the existing schemes with varying SNR values. Figure 5 shows the protection effects of the proposed UEP Scheme 1, Zhou's UEP scheme [30], and EEP Scheme 1. The coding rates of them are 0.44. Figure 6 shows the protection effects of the proposed UEP Scheme 2, Zhou's UEP scheme [30], Lakhdar's UEP scheme [14], and EEP Scheme 2. The coding rates of them are 0.47. These experimental results show that the standard deviation of the

Table 2: BER performances (1.0 dB)

Coding Rate	**0.44**			**0.47**				**0.5**				
Scheme	**EEP Scheme1**	**UEP [30]**	**Proposed Scheme1**	**EEP Scheme2**	**UEP [30]**	**UEP [14]**	**Proposed Scheme2**	**EEP Scheme3**	**UEP [30]**	**UEP [14]**	**Proposed Scheme3**	**Proposed Scheme4**
BER of PL_1	/	8.47e-3	4.71e-3	/	9.98e-3	1.20e-2	5.70e-3	/	9.41e-3	1.89e-2	1.45e-2	8.04e-3
BER of PL_2	/	1.28e-2	8.96e-3	/	2.73e-2	1.42e-2	1.70e-2	/	3.34e-2	2.19e-2	1.90e-2	2.24e-2
BER of PL_3	/	1.83e-2	1.18e-2	/	2.74e-2	1.25e-2	1.89e-2	/	3.28e-2	2.00e-2	2.01e-2	2.85e-2
BER of PL_4	/	2.10e-2	1.31e-2	/	3.12e-2	1.41e-2	1.92e-2	/	3.23e-2	2.15e-2	2.06e-2	2.43e-2
BER of PL_5	/	2.11e-2	1.43e-2	/	2.79e-2	1.25e-2	1.86e-2	/	2.98e-2	1.92e-2	2.17e-2	2.74e-2
BER of PL_6	/	2.21e-2	1.48e-2	/	3.20e-2	1.44e-2	1.93e-2	/	2.98e-2	2.13e-2	2.26e-2	2.40e-2
BER of PL_7	/	2.23e-2	1.54e-2	/	3.15e-2	1.28e-2	1.88e-2	/	3.86e-2	1.95e-2	2.49e-2	2.54e-2
BER of PL_8	/	2.26e-2	1.56e-2	/	2.65e-2	1.41e-2	1.79e-2	/	6.35e-2	2.28e-2	2.50e-2	5.50e-2
Average BER	9.43e-3	1.86e-2	1.23e-2	1.37e-2	2.67e-2	1.33e-2	1.69e-2	1.79e-2	3.37e-2	2.07e-2	2.10e-2	2.69e-2
Standard Deviation	13.77	14.72	11.48	17.62	17.69	17.23	13.72	19.88	18.25	20.45	18.45	16.17

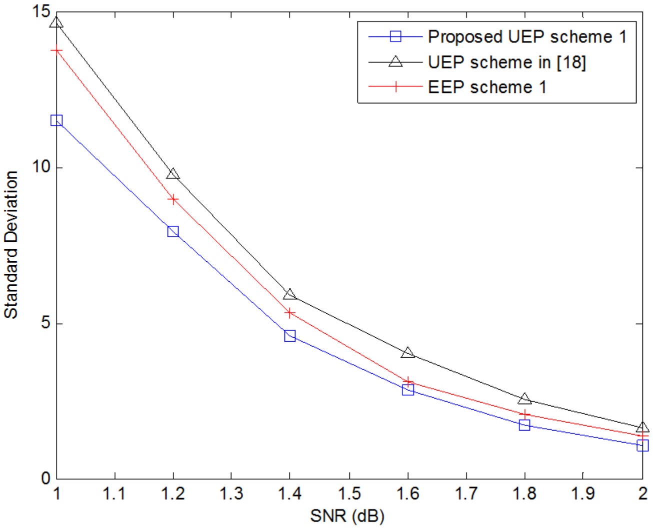

Figure 5: Standard deviation when coding rate = 0.44

proposed UEP schemes is always lower than that of the existing UEP schemes and the EEP schemes. This means that for the entire information, the protection effects of the proposed Turbo UEP schemes with flexible coding rates are better than that of the existing UEP schemes and the EEP schemes with the same coding rate.

Figure 7 shows the protection effects of the proposed UEP Schemes 3 and 4, UEP schemes in [30] and [14], and EEP Scheme 3. The coding rates of these five schemes are 0.5. The experiments show that the UEP scheme in [30] has the highest standard deviation, and the standard deviation of the UEP scheme proposed in [14] is approximately the same as that of the EEP Scheme 3. For the proposed UEP Schemes 3 and 4, the standard deviations are lower than that of the EEP Scheme 3 and Lakhdar's UEP scheme when the SNR is less than 1.4 dB. But when the SNR increases, the standard deviation of the proposed UEP Scheme 3 is approximately the same as that of the EEP Scheme 3, while the standard deviation of the proposed UEP Scheme 4 is higher than that of the EEP Scheme 3. This means that the protection effects of the proposed Turbo UEP schemes with a fixed coding rate are better than that of the existing UEP schemes and the EEP scheme only when the channel noise is high.

The following experiments show the protection effects of the proposed scheme in image transmission. Assume that the gray values of pixels vary from 0 to 255. Since each bit of a pixel's gray value has different sensitivity to channel noise, the proposed UEP Scheme 1, which has eight different protection levels, are used in the following experiments. (The puncturing controller of UEP Scheme 1 is shown as Equation (11).) Figures 8 through 10 show the experimental results. In these figures, (a) is the original image, (b) is the decoded image using the proposed UEP Scheme 1, and (c) is the decoded image using EEP Scheme 1. The SNR of the transmission channel is 1.4 dB. Table 3 shows the Peak Signal-to-Noise Ratios (PSNR) and structural similarity (SSIM) values of the decoded images using different error protection schemes. The experimental results show that although UEP Scheme 1 and EEP Scheme 1 have the same coding rate, the PSNRs of the decoded images were increased about 2 dB by the proposed UEP scheme. Meanwhile, the SSIM values of the proposed UEP scheme are higher than those of the EEP scheme, which means that the proposed UEP scheme provides better visual quality of the reconstructed images.

5 Conclusions

Two Turbo UEP schemes were proposed in this paper, both of which provide multiple protection levels for information by a one-shot coding process. In the proposed UEP schemes, the entire coding block is partitioned into several protection levels, and the coding rate of each level is controlled independently. Simulations show that for both of the proposed UEP schemes, the information bits

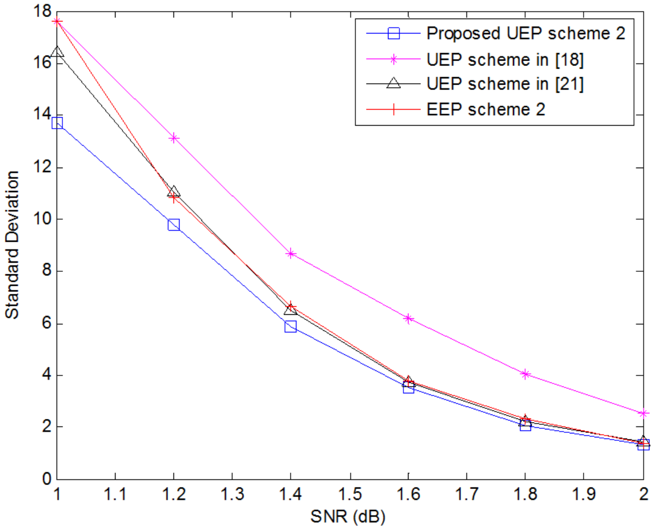

Figure 6: Standard deviation when coding rate = 0.47

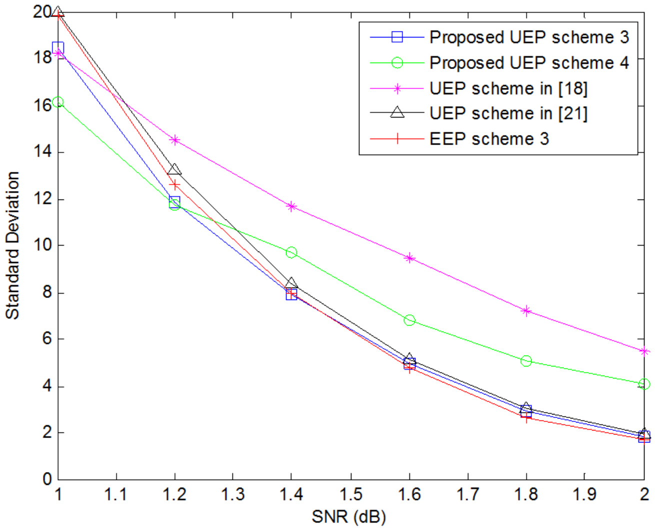

Figure 7: Standard deviation when coding rate = 0.5

Table 3: PSNRs of the decoded images using different protection schemes

	UEP Scheme 1		**EEP Scheme 1**	
Cover Image	PSNR (dB)	SSIM	PSNR (dB)	SSIM
Parrot	34.36	0.9494	32.97	0.9440
Lena	34.01	0.9542	32.04	0.9449
Baboon	34.17	0.9762	32.06	0.9667


(a) Original Image (b)Decoded Image Using UEP Scheme 1 (c)Decoded Image Using EEP Scheme 1

Figure 8: Experimental results — Parrot


(a) Original Image (b)Decoded Image Using UEP Scheme 1 (c)Decoded Image Using EEP Scheme 1

Figure 9: Experimental results — Lena

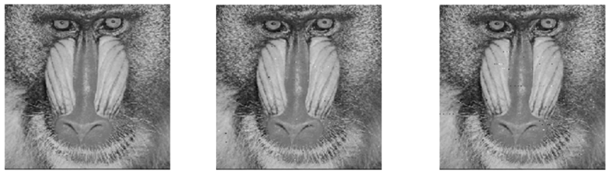
(a) Original Image (b)Decoded Image Using UEP Scheme 1 (c)Decoded Image Using EEP Scheme 1

Figure 10: Experimental results — Baboon

with a higher protection level have a lower BER than those with a lower protection level. The first proposed UEP scheme has a flexible coding rate, which is more than 1/3 and less than 1/2. The protection effect for the entire information of this scheme is always better than that of the existing Turbo UEP schemes and the Turbo EEP scheme with the same coding rate. The second proposed UEP scheme has a fixed coding rate, which is 1/2. The protection effect of this scheme is better than that of the existing UEP schemes and the EEP scheme with the same coding rate when the channel noise is high. Further works may focus on the applications of Turbo UEP schemes [6, 11, 15, 18, 19, 24, 27, 29] in different kinds of source information.

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