Unequal Protection Mechanism for Digital Speech Transimission Based on Turbo Codes

Boqing Xu[1], Qun Xiao[1], Zhenxing Qian[2], and Chuan Qin[1]
(Corresponding author: Chuan Qin)

School of Optical-Electrical and Computer Engineering, University of Shanghai for Science and Technology[1]
No. 516 Jungong Rd., Shanghai 200093, China
School of Communication and Information Engineering, Shanghai University[2]
No. 149 Yanchang Rd., Shanghai 200072, China
(Email: qin@usst.edu.cn)

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Abstract

In this paper, the Turbo-based unequal protection mechanism for reliable transmission of speech signal is studied. In order to obtain the hierarchical importance regularity of information bits for each sampling point, the changing value caused by the variation of each bit in 8-bit folded code of pulse-code modulation is first calculated. According to the obtained hierarchical importance of information bits, two unequal error protection (UEP) schemes of 3-level and 8-level are proposed based on Turbo codes. In order to achieve the satisfactory error protection capability for the global speech signal, the non-uniform puncturing is utilized in these two schemes, which can adaptively assign more parity bits for error protection to more important information bits. Compared with the traditional equal error protection (EEP) scheme, our schemes not only have greater coding rate, but also have generally better quality of the decoded speech signal on the receiver side, especially in poor channel condition. Experimental results demonstrate the effectiveness of the proposed schemes.

Keywords: Hierarchical importance, speech transmission, turbo codes, unequal protection

1 Introduction

Digital signal is usually interfered during the transmission in wireless channel, which may lead to the degradation of signal quality after decoding on the receiver side [13]. Thus, in order to decrease the error probability of information transmission, a large number of error-correcting codes (ECC), such as BCH code and Turbo code, have been proposed and used as the channel coding. Channel coding is one of the key techniques in digital communication. As a kind of channel coding, Turbo codes can be used to improve the communication quality effectively. Turbo codes provide a concatenated coding scheme and a sub-optimal iterative decoding method, which achieve excellent performances under the condition of the low channel SNR. There are many design components of Turbo codes including different encoders, input/output ratios, interleavers, and puncturing patterns. Recently, Turbo codes have been widely applied in various communication systems, such as mobile communication [11], digital video broadcasting (DVB), terrestrial wireless communication over long distances, and satellite communications (SATCOM). However, the traditional ECC can only provide the equal error protection (EEP) for each information bit. In other words, the numbers of the allocated parity bits for all information bits are the same. Actually, after the quantization and encoding for digital signals, different information bits may have different degrees of importance, and the allocation manner of parity bits for EEP may not have the global optimal performance of error protection. Therefore, the unequal error protection (UEP) for digital signals using ECC has been widely studied in recent years [3, 4, 5].

Many researchers have designed the UEP schemes using the different codes and techniques. Convolutional codes were utilized for UEP according to an algebraic theoretical viewpoint in [9]. UEP extensions of low density parity check accumulate (UEP-LDPCA) codes were discussed and several potential applications were also given in [7]. Due to the excellent performance of Turbo codes [2], there are many reported UEP schemes that were designed based on Turbo codes. Zhang *et al.* investigated the impact of different puncturing patterns on the resulting UEP properties through examining the bit error rate (BER) at various positions of a Turbo coded data block [15], and then they applied the UEP properties of Turbo codes in the transmission of JPEG2000 images. Thomos *et al.* proposed an image transmission scheme using Turbo codes for the SPIHT image streams over wireless channels [8], in which an algorithm for the optimal UEP of the compressed bit stream was also presented. An UEP method for the streaming media was proposed in [12]. In this method, besides a hierarchical coding graph, the low-complexity encoding and decoding operations were included, and the decoding probability and priority were also characterized to show the advantages of the UEP rateless codes. Morcos and Elshabrawy proposed a four-level UEP scheme for H.264 scalable video coding using discrete wavelet transform (DWT) [6], in which I-frames were provided with higher priority than P-frames. An UEP scheme based on the hierarchical quadrature amplitude modulation for the three-dimensional video transmission was presented by Alajel *et al.* [1]. In this scheme, the color sequence was assigned with more protection bits than the depth map in order to achieve the high quality of 3D video.

However, most of the reported UEP schemes were used for the transmission of digital images or videos. Speech signal is also a commonly used type of digital signals transmitted in different kinds of channel. Since the characteristics of speech signal are quite different with the signals of image and video, the corresponding coding method of speech signal is different with those of other kinds of signals. Thus, the UEP schemes in [1, 6, 8, 12] that are used for other types of signals, i.e., images and videos, can not be directly applied on the transmission protection of digital speech signal. The representative lossless coding for speech signal is the PCM coding. In computer applications, PCM coding is a commonly used method to achieve the top level of fidelity, which is widely used in audio digitization and music appreciation for CD, DVD, and audio files. On the other hand, in order to save storage space, the loss coding, such as MP3, focuses on achieving the satisfactory compression performance and the acceptable audible quality simultaneously. Although some research works were conducted on the UEP methods for the compressed speech signal [14], in this paper, we mainly focus on the error protection for uncompressed speech signals with PCM coding. Also, to the best of our knowledge, the currently reported UEP schemes are not suitable to the protection for the transmission of digital speech signal encoded by the PCM method. In this work, we propose two novel UEP schemes with three and eight protection levels for the digital speech transmission over the additive white Gaussian noise [10] (AWGN) channel. We first analyze the hierarchical importance degrees of information bits for digital speech signal after the pulse-code modulation (PCM). Then, according to the obtained rule of hierarchical importance, a new puncturing mechanism using Turbo codes is presented to achieve the capability of unequal protection for digital speech signal.

The rest of this paper is organized as follows. In Section 2, the analysis of hierarchical importance degrees of information bits after PCM speech coding is given. In Section 3, two UEP puncturing schemes based on Turbo codes are proposed. Experimental results and comparisons are presented in Section 4. Finally, conclusions are drawn in Section 5.

2 Hierarchical Importance Analysis

According to the PCM coding rule, each sampling value x of the input digital speech sequence is transformed into 8-bit folded binary code, i.e., $\{b_1, b_2, b_3, b_4, b_5, b_6, b_7, b_8\}$. $\{b_1\}$ is the sign bit. The three bits $\{b_2, b_3, b_4\}$ are called the paragraph code, which represent eight kinds of slopes for the encoded paragraphs. The decimal value of the paragraph code varies from $2^{4b_2+2b_3+b_4+3}$ to $2^{4b_2+2b_3+b_4+4}$. Here, the paragraph code {0, 0, 0} is an exception. The four bits $\{b_5, b_6, b_7, b_8\}$ are called the segment code, which represent 16 kinds of quantization levels for each encoded paragraph. Note that the sampling value x can be calculated by using its corresponding 8-bit folded binary code, i.e., $\{b_1, b_2, b_3, b_4, b_5, b_6, b_7, b_8\}$, see Equation (1).

$$x = (2b_1 - 1) \times \left[2^{\sum_{i=2}^{4} 2^{4-i} b_i + 3} + \frac{2^{\sum_{i=2}^{4} 2^{4-i} b_i + 4} - 2^{\sum_{i=2}^{4} 2^{4-i} b_i + 3}}{2^4} \times \sum_{i=5}^{8} 2^{8-i} b_i \right]. \quad (1)$$

For simplicity of the following description, we denote $2^{\sum_{i=2}^{4} 2^{4-i} b_i}$ and $\sum_{i=5}^{8} 2^{8-i} b_i$ as A and B, respectively. Clearly, A is determined by $\{b_2, b_3, b_4\}$ and B is determined by $\{b_5, b_6, b_7, b_8\}$. Thus, the sampling value x can also be represented as: $x = 8A + \frac{AB}{2}$.

During the transmission of the input speech sequence in the AWGN channel, b_i (i =1, 2, …, 8) of each sampling value x may occur errors caused by the channel noises. Therefore, before we present the UEP scheme for digital speech signal, the hierarchical importance analysis for b_i (i = 1, 2, …, 8) should be first conducted.

2.1 Analysis of the sign bit b_1

If errors occur in the sign bit b_1, the polarity of the sampling value x is inverted, and the original sampling value x is changed to $x_1 = -x = -(8A + \frac{AB}{2})$. Thus, due to the error in the sign bit b_1, the change to the sampling value x is:

$$\Delta x_1 = |x - x_1| = \left| (8A + \frac{AB}{2}) - (-8A - \frac{AB}{2}) \right| = 16A + AB. \quad (2)$$

2.2 Analysis of paragraph code $\{b_2, b_3, b_4\}$

If errors occur in b_2, the original b_2 is changed to $1 - b_2$. Thus, due to the error in b_2, the original sampling value x is changed to:

$$\begin{aligned} x_2 &= 2^{2^2(1-b_2) + \sum_{i=3}^{4} 2^{4-i} b_i + 3} + \left[\frac{2^{2^2(1-b_2) + \sum_{i=3}^{4} 2^{4-i} b_i + 4} - 2^{2^2(1-b_2) + \sum_{i=3}^{4} 2^{4-i} b_i + 3}}{2^4} \times \sum_{i=5}^{8} 2^{8-i} b_i \right] \quad (3) \\ &= 8A \times 2^{4-8b_2} + \frac{2^{4-8b_2} \times AB}{2}. \end{aligned}$$

Similarly, when errors occur in b_3 and b_4, the original sampling value x is changed to $x_3 = 8A \times 2^{2-4b_3} + \frac{2^{2-4b_3} \times AB}{2}$ and $x_4 = 8A \times 2^{1-2b_4} + \frac{2^{1-2b_4} \times AB}{2}$, respectively.

When errors occur in b_2, b_3, and b_4 separately, the changes brought to the original sampling value x can be written as Δx_2, Δx_3, and Δx_4, see Equations (4-6).

$$\Delta x_2 = |x - x_2| = \left|(8A + \frac{AB}{2}) - (8A \times 2^{4-8b_2} + \frac{2^{4-8b_2} \times AB}{2})\right| \quad (4)$$
$$= (2^{7-8b_2} - 8)A + (2^{3-8b_2} - \frac{1}{2})AB.$$

$$\Delta x_3 = |x - x_3| = \left|(8A + \frac{AB}{2}) - (8A \times 2^{2-4b_3} + \frac{2^{2-4b_3} \times AB}{2})\right| \quad (5)$$
$$= (2^{5-4b_3} - 8)A + (2^{1-4b_3} - \frac{1}{2})AB.$$

$$\Delta x_4 = |x - x_4| = \left|(8A + \frac{AB}{2}) - (8A \times 2^{1-2b_4} + \frac{2^{1-4b_4} \times AB}{2})\right| \quad (6)$$
$$= (2^{4-2b_4} - 8)A + (2^{-2b_4} - \frac{1}{2})AB.$$

Based on all possible cases of $\{b_2, b_3, b_4\}$, we can calculate the corresponding absolute differences, i.e., Δx_1, Δx_2, Δx_3, Δx_4, between the original sampling value x and the values after changing, i.e., x_1, x_2, x_3, x_4, according to Equations (2-6). It can be observed from Table 1 that, when $\{b_2, b_3, b_4\}$ belongs to {0, 0, 0}, {0, 0, 1}, {0, 1, 0}, or {0, 1, 1}, Δx_2 is greater than Δx_1, Δx_3, and Δx_4. Similarly, when $\{b_2, b_3, b_4\}$ belongs to {1, 0, 0} or {1, 0, 1}, Δx_3 become larger; and when $\{b_2, b_3, b_4\}$ belongs to {1, 1, 0} or {1, 1, 1}, Δx_1 become larger.

Table 1: Results of hierarchical importance analysis for $\{b_1, b_2, b_3, b_4\}$

$\{b_2, b_3, b_4\}$	***A***	**Δx_1**	**Δx_2**	**Δx_3**	**Δx_4**	***Relationship***
{0, 0, 0}	1	$2B$	$128+7B$	$32+B$	16	$\Delta x_2>\Delta x_3>\Delta x_1>\Delta x_4$
{0, 0, 1}	2	$32+2B$	$240+15B$	$48+3B$	16	$\Delta x_2>\Delta x_3>\Delta x_1>\Delta x_4$
{0, 1, 0}	4	$64+4B$	$480+30B$	$32+B$	$32+2B$	$\Delta x_2>\Delta x_1>\Delta x_4>\Delta x_3$
{0, 1, 1}	8	$128+8B$	$960+60B$	$48+3B$	$32+2B$	$\Delta x_2>\Delta x_1>\Delta x_3>\Delta x_4$
{1, 0, 0}	16	$256+16B$	$128+7B$	$384+24B$	$128+8B$	$\Delta x_3>\Delta x_1>\Delta x_4>\Delta x_2$
{1, 0, 1}	32	$512+32B$	$240+15B$	$768+48B$	$128+8B$	$\Delta x_3>\Delta x_1>\Delta x_2>\Delta x_4$
{1, 1, 0}	64	$1024+64B$	$480+30B$	$384+24B$	$512+32B$	$\Delta x_1>\Delta x_4>\Delta x_2>\Delta x_3$
{1, 1, 1}	128	$2048+128B$	$960+60B$	$768+48B$	$512+32B$	$\Delta x_1>\Delta x_2>\Delta x_3>\Delta x_4$

In general, the statistical distribution of amplitude for the long-term speech signal (more than dozens of seconds) is close to Gamma distribution, while the statistical distribution of amplitude for the short-term speech signal (several to dozens of milliseconds) is close to Gaussian distribution. Whether the duration of the speech signal is long or short, the occurrence probability of the small amplitude is greater than that of the large one, see Figure 1. In other words, the probability for $\{b_2, b_3, b_4\}$ belonging to {0, 0, 0}, {0, 0, 1}, {0, 1, 0}, and {0, 1, 1} is greater than that belonging to {1, 0, 0}, {1, 0, 1}, {1, 1, 0}, and {1, 1, 1}. Therefore, from a statistical point of view, we can conclude that the regularity of the hierarchical importance for $\{b_1, b_2, b_3, b_4\}$ is: $I(b_2) > I(b_1) > I(b_3) > I(b_4)$, where $I(\cdot)$ denotes the function of importance degree.

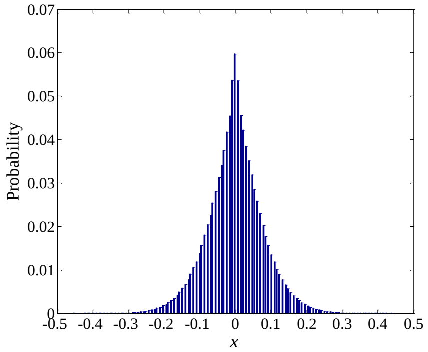


Figure 1: The statistical distribution of amplitude for one digital speech signal

2.3 Analysis of segment code $\{b_5, b_6, b_7, b_8\}$

In order to analyze the importance degree of $\{b_5, b_6, b_7, b_8\}$, the sampling value x in Equation (1) can be represented in the form of Equation (7).

$$x = (8 + \sum_{i=5}^{8} 2^{7-i} b_i)A. \quad (7)$$

If errors occur in b_5, $(1 - b_5)$ is just the changed value of b_5. Consequently, the changed sampling value due to the variation of b_5 is:

$$x_5 = \left[4(1-b_5) + \sum_{i=6}^{8} 2^{7-i} b_i + 8\right]A = (-4b_5 + \sum_{i=6}^{8} 2^{7-i} b_i + 12)A. \quad (8)$$

In the same way, when errors occur in b_6, b_7, and b_8, the changed sampling values x_6, x_7, and x_8 can be calculated using Equations (9-11), respectively.

$$x_6 = (-2b_6 + \sum_{i=5,7,8} 2^{7-i} b_i + 10)A. \quad (9)$$

$$x_7 = (-b_7 + \sum_{i=5,6,8} 2^{7-i} b_i + 9)A. \quad (10)$$

$$x_8 = (-\frac{1}{2} b_8 + \sum_{i=5}^{7} 2^{7-i} b_i + \frac{17}{2})A. \quad (11)$$

When the channel errors occur in b_5, b_6, b_7, and b_8 separately, the corresponding absolute differences, i.e., Δx_5,

Δx_6, Δx_6, Δx_8, between the original sampling value x and the values after changing, i.e., x_5, x_6, x_7, x_8, can be calculated according to Equations (12-15).

$$\Delta x_5 = |x - x_5| = \left|(8+\sum_{i=5}^{8} 2^{7-i} b_i)A - (-4b_5 + \sum_{i=6}^{8} 2^{7-i} b_i + 12)A\right| = |8b_5 - 4|A. \tag{12}$$

$$\Delta x_6 = |x - x_6| = \left|(8+\sum_{i=5}^{8} 2^{7-i} b_i)A - (-2b_6 + \sum_{i=5,7,8} 2^{7-i} b_i + 10)A\right| = |4b_6 - 2|A. \tag{13}$$

$$\Delta x_7 = |x - x_7| = \left|(8+\sum_{i=5}^{8} 2^{7-i} b_i)A - (-b_7 + \sum_{i=5,6,8} 2^{7-i} b_i + 9)A\right| = |2b_7 - 1|A. \tag{14}$$

$$\Delta x_8 = |x - x_8| = \left|(8+\sum_{i=5}^{8} 2^{7-i} b_i)A - (-\frac{1}{2}b_8 + \sum_{i=5}^{7} 2^{7-i} b_i + \frac{17}{2})A\right| = \left|b_8 - \frac{1}{2}\right|A. \tag{15}$$

Since the binary bits b_5, b_6, b_7, b_8 are either 0 or 1, thus, Δx_5, Δx_6, Δx_7, and Δx_8 in Equations (12-15) can be written as: $\Delta x_5 = 4A$, $\Delta x_6 = 2A$, $\Delta x_7 = A$, $\Delta x_8 = 1/2A$. It can be clearly found that, when errors occur in $\{b_5, b_6, b_7, b_8\}$ separately, the absolute differences between the original sampling value and the corresponding values after changing show a decreasing trend. In other words, the regularity of the hierarchical importance for $\{b_5, b_6, b_7, b_8\}$ is: $I(b_5) > I(b_6) > I(b_7) > I(b_8)$.

Because Δx_5 is equal to $4A$, we can observe from Table 1 that, Δx_4 is always greater than Δx_5 with all possible values of A. Therefore, based on the above analysis, for the 8-bit folded binary code $\{b_1, b_2, b_3, b_4, b_5, b_6, b_7, b_8\}$ of each sampling point x in the speech signal, the two bits b_2 and b_1 have the first and the second highest importance degree, and the whole regularity of the hierarchical importance is: $I(b_2) > I(b_1) > I(b_3) > I(b_4) > I(b_5) > I(b_6) > I(b_7) > I(b_8)$.

3 Proposed UEP Schemes Using Turbo Codes

Based on the results of hierarchical importance analysis in Section 2, a novel unequal protection mechanism for digital speech signal using Turbo codes is presented. The framework diagram of the Turbo-based unequal protection mechanism is illustrated in Figure 2.

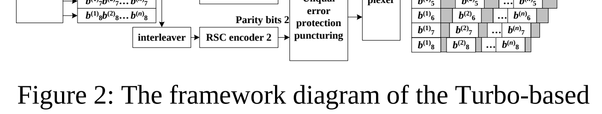


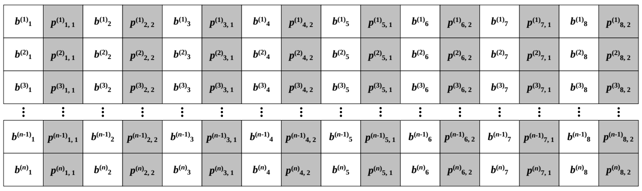
Figure 2: The framework diagram of the Turbo-based unequal protection mechanism

Suppose that the digital speech signal **X** for protection is $x^{(1)}, x^{(2)}, \ldots, x^{(n)}$, where n denotes the length of the signal, i.e., the number of sampling points. During the PCM coding, each sampling point $x^{(i)}$ of **X** is encoded to a string of 8-bit folded binary code, i.e., $b^{(i)}_1, b^{(i)}_2, \ldots, b^{(i)}_8$, $i = 1, 2, \ldots, n$. Thus, the total number of the concentrated binary bits after PCM coding for the speech signal **X** is $8n$. Before conducting the unequal protection by Turbo codes, we first divide the total $8n$-bit binary sequence of **X** into eight groups, and the j^{th} group $\mathbf{G}_j$ consists of the n elements: $\{b^{(1)}_j, b^{(2)}_j, \ldots, b^{(n)}_j\}$, $j = 1, 2, \ldots, 8$. Then, we concentrate the $8n$ bits in these eight groups sequentially and feed them into the Turbo encoder. In the procedure of Turbo encoding, one copy of the $8n$ bits is inputted into the first recursive systemic convolutional (RSC) encoder, and the output is treated as the first group of $8n$ parity bits. The second copy of the $8n$ bits is first messed up by the interleaver and then inputted into the second RSC encoder, and the output is treated as the second group of $8n$ parity bits. The two groups of parity bits outputted from RSC encoders are utilized to provide the error protection for the information bits. Different with traditional Turbo codes of EEP, in order to achieve the UEP capability, we adopt the non-uniform puncturing for the two groups of parity bits. The punctured parity bits are sent to the multiplexer together with the $8n$ information bits, and the output of the multiplexer is the final encoded bits with the unequal protection, which can be transmitted in the channel. The shaded parts in Figure 2 represent the assigned parity bits for the information bits after puncturing. The longer the shaded parts are, the higher protection level they provide. Because the hierarchical importance degrees of information bits are considered, the global error protection performance of UEP is better than that of EEP under the same coding rate.

Note that the puncturing method is the key of the framework in Figure 2, and the different puncturing methods correspond to different error protection schemes. In the following, we propose two non-uniform puncturing methods that can achieve 3-level and 8-level protection for the digital speech signal, respectively.

3.1 3-Level Protection Scheme

The traditional uniform puncturing method can only achieve the EEP capability. In other words, the uniform puncturing of EEP considers that the total information bits have the equal importance degree. Detailedly, in the uniform puncturing of EEP, each information bit has two parity bits, i.e., $p^{(i)}_{j,1}$ and $p^{(i)}_{j,2}$, initially ($i = 1, 2, \ldots, n$, $j = 1, 2, \ldots, 8$). If the information bit locates in the odd position j, its second parity bit $p^{(i)}_{j,2}$ is removed and its first parity bit $p^{(i)}_{j,1}$ is kept as its unique parity bit, while if the information bit locates in the even position j, its first parity bit $p^{(i)}_{j,1}$ is removed and its second parity bit $p^{(i)}_{j,2}$ is kept as its unique parity bit, see Figure 3. Thus, after the uniform puncturing of EEP, each information bit has only one parity bit, and the coding rate is 1/2 consequently. However, only one protection level can be provided by the uniform puncturing of EEP, which can not meet the practical requirement. A UEP scheme with 3-level protection through the non-uniform puncturing is given as follows, which can also improve the performance of coding rate.

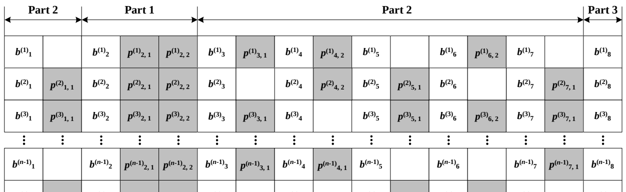


$b^{(1)}_1$	$p^{(1)}_{1,1}$	$b^{(1)}_2$	$p^{(1)}_{2,2}$	$b^{(1)}_3$	$p^{(1)}_{3,1}$	$b^{(1)}_4$	$p^{(1)}_{4,2}$	$b^{(1)}_5$	$p^{(1)}_{5,1}$	$b^{(1)}_6$	$p^{(1)}_{6,2}$	$b^{(1)}_7$	$p^{(1)}_{7,1}$	$b^{(1)}_8$	$p^{(1)}_{8,2}$
$b^{(2)}_1$	$p^{(2)}_{1,1}$	$b^{(2)}_2$	$p^{(2)}_{2,2}$	$b^{(2)}_3$	$p^{(2)}_{3,1}$	$b^{(2)}_4$	$p^{(2)}_{4,2}$	$b^{(2)}_5$	$p^{(2)}_{5,1}$	$b^{(2)}_6$	$p^{(2)}_{6,2}$	$b^{(2)}_7$	$p^{(2)}_{7,1}$	$b^{(2)}_8$	$p^{(2)}_{8,2}$
$b^{(3)}_1$	$p^{(3)}_{1,1}$	$b^{(3)}_2$	$p^{(3)}_{2,2}$	$b^{(3)}_3$	$p^{(3)}_{3,1}$	$b^{(3)}_4$	$p^{(3)}_{4,2}$	$b^{(3)}_5$	$p^{(3)}_{5,1}$	$b^{(3)}_6$	$p^{(3)}_{6,2}$	$b^{(3)}_7$	$p^{(3)}_{7,1}$	$b^{(3)}_8$	$p^{(3)}_{8,2}$
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
$b^{(n-1)}_1$	$p^{(n-1)}_{1,1}$	$b^{(n-1)}_2$	$p^{(n-1)}_{2,2}$	$b^{(n-1)}_3$	$p^{(n-1)}_{3,1}$	$b^{(n-1)}_4$	$p^{(n-1)}_{4,2}$	$b^{(n-1)}_5$	$p^{(n-1)}_{5,1}$	$b^{(n-1)}_6$	$p^{(n-1)}_{6,2}$	$b^{(n-1)}_7$	$p^{(n-1)}_{7,1}$	$b^{(n-1)}_8$	$p^{(n-1)}_{8,2}$
$b^{(n)}_1$	$p^{(n)}_{1,1}$	$b^{(n)}_2$	$p^{(n)}_{2,2}$	$b^{(n)}_3$	$p^{(n)}_{3,1}$	$b^{(n)}_4$	$p^{(n)}_{4,2}$	$b^{(n)}_5$	$p^{(n)}_{5,1}$	$b^{(n)}_6$	$p^{(n)}_{6,2}$	$b^{(n)}_7$	$p^{(n)}_{7,1}$	$b^{(n)}_8$	$p^{(n)}_{8,2}$

Figure 3: The result of the uniform puncturing of EEP

According to the results of the hierarchical importance analysis in Section 2, the second bit $b^{(i)}_2$ of the 8-bit folded binary code for each sampling point $x^{(i)}$ in $\mathbf{X}$ has the highest importance degree, and the eighth bit $b^{(i)}_8$ has the lowest importance degree (i = 1, 2, …, n). Therefore, in the proposed 3-level protection scheme, we define that the n bits of $b^{(i)}_2$ for all n sampling points in $\mathbf{X}$ are provided with the highest protection level, i.e., level 1, while the n bits of $b^{(i)}_8$ are provided with the lowest protection level, i.e., level 3. The remaining 6n information bits including $b^{(i)}_1$, $b^{(i)}_3$, $b^{(i)}_4$, $b^{(i)}_5$, $b^{(i)}_6$, and $b^{(i)}_7$, are considered as a whole and provided with the middle protection level, i.e., level 2.

During the non-uniform puncturing process, each of the n bits $b^{(i)}_2$ for all n sampling points in $\mathbf{X}$ is always assigned with two parity bits, i.e., $p^{(i)}_{2,1}$ and $p^{(i)}_{2,2}$, for error protection (i = 1, 2, …, n), see Part 1 in Figure 4, and each of the n bits $b^{(i)}_8$ is always assigned with no parity bits, see Part 3 in Figure 4. For the 6n information bits belonging to level 2, $6n - m$ parity bits are assigned randomly ($0 \le m < 6n$), and each bit belonging to level 2 is assigned with no more than one parity bit, see Part 2 in Figure 4. That is to say, after puncturing, m information bits belonging to level 2 have no parity bits, and each of the other $6n - m$ information bits has one parity bit. Statistically, each information bit belonging to level 1, 2, and 3 is assigned with 2, $(6n - m)/6n$, and 0 parity bits for error protection, respectively. Thus, more important the information bit is, more parity bits are assigned for error protection.



Part 2		Part 1			Part 2										Part 3
$b^{(1)}_1$		$b^{(1)}_2$	$p^{(1)}_{2,1}$	$p^{(1)}_{2,2}$	$b^{(1)}_3$	$p^{(1)}_{3,1}$	$b^{(1)}_4$	$p^{(1)}_{4,2}$	$b^{(1)}_5$		$b^{(1)}_6$	$p^{(1)}_{6,2}$	$b^{(1)}_7$		$b^{(1)}_8$
$b^{(2)}_1$	$p^{(2)}_{1,1}$	$b^{(2)}_2$	$p^{(2)}_{2,1}$	$p^{(2)}_{2,2}$	$b^{(2)}_3$		$b^{(2)}_4$	$p^{(2)}_{4,2}$	$b^{(2)}_5$	$p^{(2)}_{5,1}$	$b^{(2)}_6$		$b^{(2)}_7$	$p^{(2)}_{7,1}$	$b^{(2)}_8$
$b^{(3)}_1$	$p^{(3)}_{1,1}$	$b^{(3)}_2$	$p^{(3)}_{2,1}$	$p^{(3)}_{2,2}$	$b^{(3)}_3$	$p^{(3)}_{3,1}$	$b^{(3)}_4$		$b^{(3)}_5$	$p^{(3)}_{5,1}$	$b^{(3)}_6$	$p^{(3)}_{6,2}$	$b^{(3)}_7$	$p^{(3)}_{7,1}$	$b^{(3)}_8$
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
$b^{(n-1)}_1$		$b^{(n-1)}_2$	$p^{(n-1)}_{2,1}$	$p^{(n-1)}_{2,2}$	$b^{(n-1)}_3$	$p^{(n-1)}_{3,1}$	$b^{(n-1)}_4$	$p^{(n-1)}_{4,1}$	$b^{(n-1)}_5$		$b^{(n-1)}_6$		$b^{(n-1)}_7$	$p^{(n-1)}_{7,1}$	$b^{(n-1)}_8$
$b^{(n)}_1$	$p^{(n)}_{1,1}$	$b^{(n)}_2$	$p^{(n)}_{2,1}$	$p^{(n)}_{2,2}$	$b^{(n)}_3$		$b^{(n)}_4$		$b^{(n)}_5$	$p^{(n)}_{5,1}$	$b^{(n)}_6$	$p^{(n)}_{6,2}$	$b^{(n)}_7$		$b^{(n)}_8$

Figure 4: The result of the non-uniform puncturing of UEP with 3-level protection

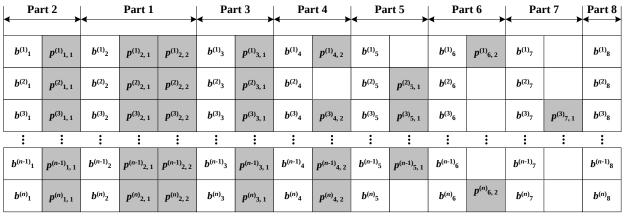
In the proposed 3-level protection scheme, there are totally $8n - m$ parity bits assigned to the 8n information bits of three protection levels. Clearly, the coding rate is $8n/(16n - m)$ after this non-uniform puncturing of UEP with 3-level protection, which is always not smaller than that of the EEP scheme.

3.2 8-Level Protection Scheme

In this subsection, we propose a UEP scheme with 8-level protection for the speech signal $\mathbf{X}$, which can achieve more hierarchical protection than the 3-level scheme. As stated in Section 2, the hierarchical importance of the 8-bit folded binary code for each sampling point $x^{(i)}$ in $\mathbf{X}$ is: $\mathrm{I}(b^{(i)}_2) > \mathrm{I}(b^{(i)}_1) > \mathrm{I}(b^{(i)}_3) > \mathrm{I}(b^{(i)}_4) > \mathrm{I}(b^{(i)}_5) > \mathrm{I}(b^{(i)}_6) > \mathrm{I}(b^{(i)}_7) > \mathrm{I}(b^{(i)}_8)$, ($i$ = 1, 2, …, n). Thus, similar with the 3-level scheme, in the proposed 8-level protection scheme, we define that the n bits of $b^{(i)}_2$ for all n sampling points in $\mathbf{X}$ have the highest protection level, i.e., level 1, and the n bits of $b^{(i)}_8$ have the lowest protection level, i.e., level 8. The n bits of $b^{(i)}_1$ are defined to belong to level 2, and the n bits of $b^{(i)}_j$ are defined to belong to level j (j = 3, 4, 5, 6, 7). Therefore, totally 8 protection levels are defined, and each protection level has n information bits.

During the non-uniform puncturing process, each of the n bits $b^{(i)}_2$ belonging to level 1 is always assigned with two parity bits, i.e., $p^{(i)}_{2,1}$ and $p^{(i)}_{2,2}$, for error protection (i = 1, 2, …, n), see Part 1 in Figure 5, and each of the n bits $b^{(i)}_8$ belonging to level 8 is always assigned with no parity bits, see Part 8 in Figure 5. For the n bits $b^{(i)}_1$ belonging to level 2, $n - m_1$ parity bits are assigned randomly, and each bit belonging to level 2 is assigned with no more than one parity bit, see Part 2 in Figure 5. Similarly, for the n bits $b^{(i)}_j$ belonging to level j (j = 3, 4, 5, 6, 7), $n - m_j$ parity bits are assigned randomly, and each bit belonging to level j is assigned with no more than one parity bit, see Part 3-7 in Figure 5. That is to say, after puncturing, m_1 information bits belonging to level 2 have no parity bits, and each of the other $n - m_1$ bits has one parity bit; m_j information bits belonging to level j have no parity bits, and each of the other $n - m_j$ bits has one parity bit (j = 3, 4, 5, 6, 7). Note that the following relationship should be satisfied to achieve the UEP capability and be consistent with the result of hierarchical importance analysis in Section 2.

$$0 \le m_1 \le m_3 \le m_4 \le m_5 \le m_6 \le m_7 < n. \tag{16}$$



Part 2		Part 1			Part 3		Part 4		Part 5		Part 6		Part 7		Part 8
$b^{(1)}_1$	$p^{(1)}_{1,1}$	$b^{(1)}_2$	$p^{(1)}_{2,1}$	$p^{(1)}_{2,2}$	$b^{(1)}_3$	$p^{(1)}_{3,1}$	$b^{(1)}_4$	$p^{(1)}_{4,2}$	$b^{(1)}_5$		$b^{(1)}_6$	$p^{(1)}_{6,2}$	$b^{(1)}_7$		$b^{(1)}_8$
$b^{(2)}_1$	$p^{(2)}_{1,1}$	$b^{(2)}_2$	$p^{(2)}_{2,1}$	$p^{(2)}_{2,2}$	$b^{(2)}_3$	$p^{(2)}_{3,1}$	$b^{(2)}_4$		$b^{(2)}_5$	$p^{(2)}_{5,1}$	$b^{(2)}_6$		$b^{(2)}_7$		$b^{(2)}_8$
$b^{(3)}_1$	$p^{(3)}_{1,1}$	$b^{(3)}_2$	$p^{(3)}_{2,1}$	$p^{(3)}_{2,2}$	$b^{(3)}_3$	$p^{(3)}_{3,1}$	$b^{(3)}_4$	$p^{(3)}_{4,2}$	$b^{(3)}_5$	$p^{(3)}_{5,1}$	$b^{(3)}_6$		$b^{(3)}_7$	$p^{(3)}_{7,1}$	$b^{(3)}_8$
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
$b^{(n-1)}_1$	$p^{(n-1)}_{1,1}$	$b^{(n-1)}_2$	$p^{(n-1)}_{2,1}$	$p^{(n-1)}_{2,2}$	$b^{(n-1)}_3$	$p^{(n-1)}_{3,1}$	$b^{(n-1)}_4$	$p^{(n-1)}_{4,2}$	$b^{(n-1)}_5$	$p^{(n-1)}_{5,1}$	$b^{(n-1)}_6$		$b^{(n-1)}_7$		$b^{(n-1)}_8$
$b^{(n)}_1$	$p^{(n)}_{1,1}$	$b^{(n)}_2$	$p^{(n)}_{2,1}$	$p^{(n)}_{2,2}$	$b^{(n)}_3$	$p^{(n)}_{3,1}$	$b^{(n)}_4$	$p^{(n)}_{4,2}$	$b^{(n)}_5$		$b^{(n)}_6$	$p^{(n)}_{6,2}$	$b^{(n)}_7$		$b^{(n)}_8$

Figure 5: The result of the non-uniform puncturing of UEP with 8-level protection

Consequently, according to Equation (16), more important the information bit is, more parity bits are assigned for error protection. Statistically, each information bit belonging to level 1 and level 2 is assigned with 2 and $(n - m_1)/n$ parity bits for error protection, respectively; each information bit belonging to level j is assigned with $(n - m_j)/n$ parity bits (j = 3, 4, 5, 6, 7), and no parity bits are assigned to the information bits belonging to level 8. Here, for simplicity, we make the summation of m_j (j = 1, 3, 4, 5, 6, 7) be equal to the value m in the 3-level scheme, see Equation (17). Thus, the coding rate of the proposed 8-level protection scheme is also $8n/(16n-m)$, which is equal to that of 3-level protection scheme.

$$m_1 + \sum_{j=3}^{7} m_j \equiv m. \tag{17}$$

3.3 Analysis of 3-Level and 8-Level UEP Schemes

The two Turbo-based schemes proposed above both utilize the non-uniform puncturing method to achieve the UEP capability and provide the hierarchical protection to the information bits of the speech signal. Compared with the EEP scheme described in Figure 3, the UEP schemes shown in Figures 4-5 make full use of the characteristics of speech signal, i.e., the sign bit, 3 bits in paragraph code, and 4 bits in segment code have different importance degrees, to achieve better performance.

The 3-level UEP scheme divides the importance degree into 3 parts, which makes the encoding and decoding procedures easier to implement compared with the 8-level UEP scheme. In other words, the 3-level UEP scheme can achieve a compromise of simple encoding/decoding structure and good protection capability considering the speech signal characteristics, which is more suitable for real-time applications. The 8-level UEP scheme divides the importance degree into 8 parts, and its encoding and decoding procedures are more complicated compared with the 3-level UEP scheme. But, the 8-level UEP scheme take full advantage of the hierarchical importance of the speech signal and can achieve better protection capability than the EEP scheme and the proposed 3-level UEP scheme, which is more suitable for the communication system requiring higher reliability.

4 Experimental Results and Comparisons

Experiments were conducted on a large number of the digital speech signals to evaluate the performances of our unequal protection schemes. All experiments were implemented on a computer with 2.40 GHz Intel Core 2 Quad Q6600 processor, 3.00 GB memory, and Windows 7 operating system. Due to the extensive data of sampling points, the whole speech signal was divided into several segments with the equal length, and the error protection scheme was carried on each segment independently. Average segment signal-to-noise ratio (ASSNR) was utilized to evaluate the quality of the speech signal. The average value of the segment signal-to-noise ratio, i.e., ASSNR, for all segments of the speech signal can be calculated according to Equation (18).

$$\mathrm{ASSNR} = \frac{1}{K}\sum_{k=1}^{K} 10 \times \log_{10}\left\{\frac{\sum_{i=1}^{n} X_k^2(i)}{\sum_{i=1}^{n}\left[X_k(i) - X'_k(i)\right]^2}\right\}, \tag{18}$$

where K is total number of the divided segments for the whole speech signal, n is the number of sampling points in each speech segment, $X_k(i)$ and $X'_k(i)$ are the i^{th} sampling point values of the k^{th} segment for the original input speech signal on the sender side and the decoded signal on the receiver side, respectively. Obviously, the greater the value of ASSNR is, the better the quality of the received speech signal is. Experimental configurations are listed in Table 2.

We first compared the coding rate performances between the traditional Turbo-based EEP scheme and our proposed UEP schemes. As stated above, in the traditional Turbo-based EEP scheme, after the uniform puncturing, each information bit has one parity bit, thus, the coding rate is fixed to 1/2. For our proposed 3-level and 8-level UEP schemes, the coding rates both are $8n/(16n-m)$, which is related to the parameter m ($0 \le m < 6n$) in the non-uniform puncturing process. The value m denotes the number of bits $\{b^{(i)}_1, b^{(i)}_3, b^{(i)}_4, b^{(i)}_5, b^{(i)}_6, b^{(i)}_7\}$ assigned with no parity bits in each segment of the speech signal (i = 1, 2, …, n). Figure 6 shows the results of the coding rates for the EEP scheme and the proposed UEP scheme. It can be observed from Figure 6 that the coding rate of the proposed UEP scheme increases with m and is always not smaller than that of the EEP scheme, which demonstrates that the proposed scheme has better performance of the encoding efficiency than the EEP scheme. Note that, with the increase of m, the error protection capability of our scheme for the speech signal could decrease gradually. Thus, in the following, the performances of error protection were also compared.

Table 2: Experimental configurations

Parameters	***Values***
Data transmission channel	AWGN channel
Channel SNRs	E_b/N_0 = 0.6dB, 0.8dB, 1.0dB, 1.2dB
Interleaver	Pseudo-random interleaver
Number of sampling points in each segment	n = 64
Decoding algorithm	Log-MAP

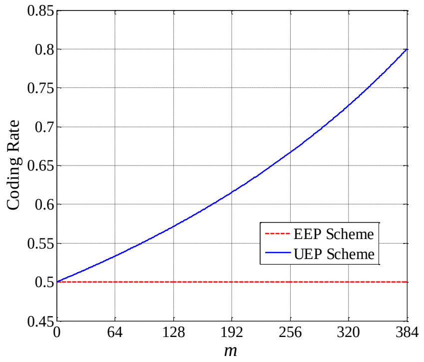
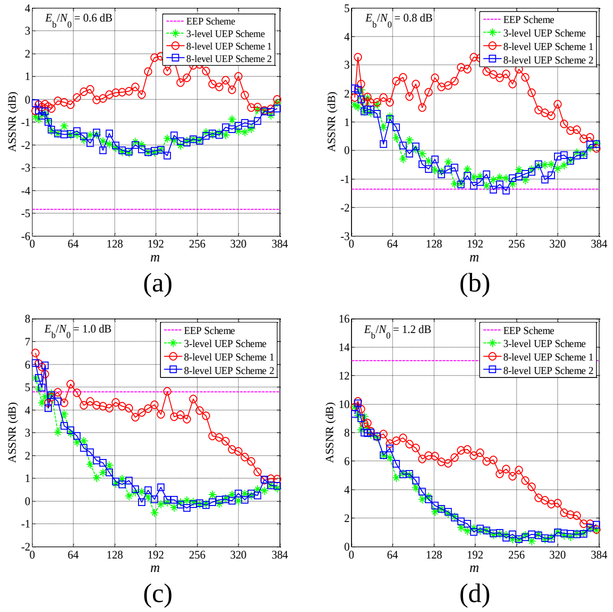


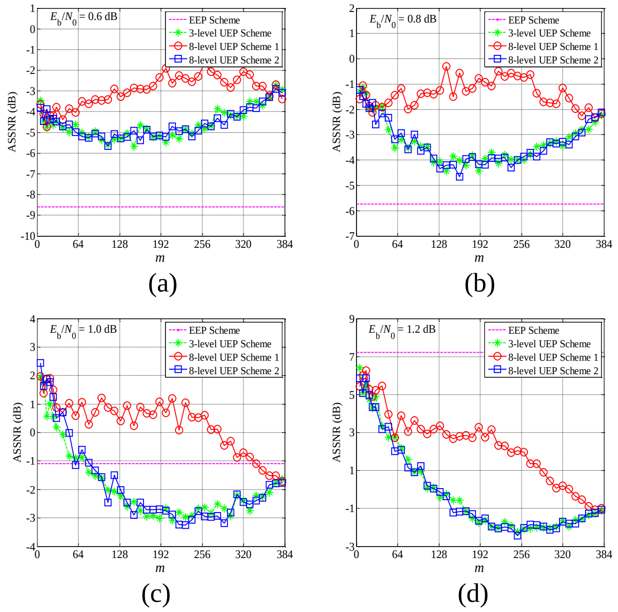
Figure 6: Comparisons of the coding rate between the traditional Turbo-based EEP scheme and our proposed UEP scheme



(a) (b)

(c) (d)

Figure 7: Comparison results of error protection performances under different channel SNRs for speech signal 1. (a) E_b/N_0 = 0.6 dB, (b) E_b/N_0 = 0.8 dB, (c) E_b/N_0 = 1.0 dB, (d) E_b/N_0 = 1.2 dB.

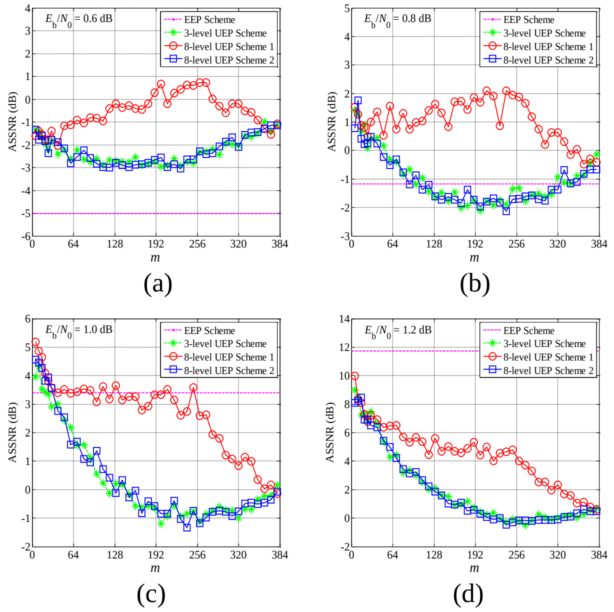


(a) (b)

(c) (d)

Figure 8: Comparison results of error protection performances under different channel SNRs for speech signal 2. (a) E_b/N_0 = 0.6 dB, (b) E_b/N_0 = 0.8 dB, (c) E_b/N_0 = 1.0 dB, (d) E_b/N_0 = 1.2 dB.

Figures 7-9 show the comparison results of error protection performances among traditional Turbo-based EEP scheme, proposed 3-level UEP scheme, and proposed 8-level UEP scheme. Figures 7, 8, and 9 correspond to the results of three typical speech signals, i.e., man.wav (male voice), woman.wav (female voice), and music.wav (female song), and each signal was tested under four different channel SNRs E_b/N_0, i.e., 0.6 dB, 0.8 dB, 1.0 dB, and 1.2 dB, respectively. The three digital speech signals all have the durations of 8 seconds, and the used sampling frequency was 8 KHz, which means there are 64,000 sampling points in each signal. Because n was set to 64 in the experiments, each signal was divided into 1,000 segments, i.e., K =1000. Note that, for a given value of m in the proposed 8-level UEP scheme, there are possibly a large number of solutions for m_j (j = 1, 3, 4, 5, 6, 7) to meet the relationships in Equations (16-17). In Figures 7-9, the curves of 8-level UEP scheme 1 correspond to a randomly chosen group of m_1, m_3, m_4, m_5, m_6, m_7 that are satisfied with Equations (16-17), and the curves of 8-level UEP scheme 2 correspond to a specific group of m_1, m_3, m_4, m_5, m_6, m_7 that have the equal value, i.e., m/6. Thus, for a statistical point of view, 8-level UEP scheme 2 is equivalent to the 3-level UEP scheme.



(a) (b)

(c) (d)

Figure 9: Comparison results of error protection performances under different channel SNRs for speech signal 3. (a) E_b/N_0 = 0.6 dB, (b) E_b/N_0 = 0.8 dB, (c) E_b/N_0 = 1.0 dB, (d) E_b/N_0 = 1.2 dB.

Because hierarchical importance degrees of information bits are considered during the puncturing process of parity bits, some conclusions can be acquired from the results of Figures 6-9. (1) For each speech signal, when the channel SNR, i.e., E_b/N_0, increases, the ASSNAR value always becomes greater. It means that ASSNR value is directly proportional to E_b/N_0. (2) When m = 0, i.e., no parity bits are punctured from each information bit of $\{b^{(i)}_1, b^{(i)}_3, b^{(i)}_4, b^{(i)}_5, b^{(i)}_6, b^{(i)}_7\}$, the coding rate is 1/2 and the ASSNR value is the peak value of each curve. When m = 384, i.e., all parity bits are punctured from all information bits, the coding rate is the maximum value and the ASSNR value is the valley value of each curve. No matter m equals 0 or 384, the curves of the 3-level UEP scheme and the 8-level UEP scheme intersect at a point for the reason that their parity bits are at the same state, i.e., the second information bit with two parity bits and the eighth information bit with no parity bits. E_b/N_0 and ASSNR value have no linear relationship with the change of m due to the random puncturing for the parity bits. Our two proposed UEP schemes not only have better error protection performance than the traditional Turbo codes of EEP, but also have greater coding rate, which means the higher transmission efficiency of our schemes. (3) For each given value of m, the 8-level UEP scheme 1 always performs better than the 8-level UEP scheme 2 due to the different distributions of m for the two schemes. When m is divided evenly into 6 parts according to 8-level UEP scheme 2, the parity bits of information bits $\{b^{(i)}_1, b^{(i)}_3, b^{(i)}_4, b^{(i)}_5, b^{(i)}_6, b^{(i)}_7\}$ are punctured equally. However, when m is divided into 6 parts according to the puncturing method of the 8-level UEP scheme 1, the parity bits are mainly punctured from the latter part of information bits $\{b^{(i)}_1, b^{(i)}_3, b^{(i)}_4, b^{(i)}_5, b^{(i)}_6, b^{(i)}_7\}$ and the parity bits of the former part of information bits are retained, which leads to better quality of the decoded speech signal. (4) Under the lower channel SNRs, the two proposed 8-level and 3-level UEP schemes generally have better performances of error protection than the traditional Turbo-based EEP scheme with respect to ASSNR. Due to the strategy of more hierarchical protection, 8-level UEP scheme is superior to 3-level UEP scheme. However, when the channel condition and SNRs become better, the superiority of the proposed UEP schemes is not significant compared with the EEP scheme, even though their coding rates are always greater than that of the EEP scheme, which demonstrates the proposed 8-level and 3-level UEP schemes are more suitable to be applied in the poor transmission condition.

5 Conclusions

Two novel unequal protection schemes for digital speech transmission are proposed in this paper. By calculating the changing value for the amplitude of each sampling point, the hierarchical importance analysis for each information bit in the 8-bit PCM code is first conducted. Then, according to the acquired regularity of hierarchical importance, two Turbo-based UEP schemes with 3-level and 8-level protection capability are designed for the reliable speech transmission through the non-uniform puncturing mechanism. Because more important information bits are adaptively assigned with more parity bits in the two proposed scheme, the performances of error protection for the speech signal are generally better than that of the traditional Turbo-based EEP scheme, especially in the poor channel condition with lower SNR. Additionally, the coding rate of our UEP schemes is always greater than that of the EEP scheme. Future investigations include how to obtain the optimal assignment of parity bits with higher efficiency in non-uniform puncturing process.

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Boqing Xu received the B.S. degree in Communication Engineering from Dalian Maritime University in 1982 and the M.S. degree in Industrial Automation from Shandong University in 1987. In 2003, he received the Ph.D. degree Patten Recognition and Artificial Intelligence from Tongji University, Shanghai, China. Currently, he has been with the faculty of the School of Optical-Electrical and Computer Engineering, University of Shanghai for Science and Technology, where he is currently an Associate Professor. His research interests include signal processing and optimization theory.

Qun Xiao received the B.S. degree in Science and Technology of Electronic Information from Hubei University of Art and Science, Hubei, China, in 2011. She is currently pursuing the M.S. degree in Signal and Information Processing from University of Shanghai for Science and Technology, Shanghai, China. Her research interests include signal processing and data coding.

Zhenxing Qian received the B.S. and Ph.D. degrees from the University of Science and Technology of China (USTC), Hefei, China, in 2003 and 2007, respectively. Since 2009, he has been with the faculty of the School of Communication and Information Engineering, Shanghai University, where he is currently an Associate Professor. His research interests include signal processing, data hiding, and digital forensics.

Chuan Qin received the B.S. and M.E. degrees in Electronic Engineering from the Hefei University of Technology, Anhui, China, in 2002 and 2005, respectively, and the Ph.D. degree in signal and information processing from Shanghai University, Shanghai, China, in 2008. Since 2008, he has been with the faculty of the School of Optical-Electrical and Computer Engineering, University of Shanghai for Science and Technology, where he is currently a Lecturer. He also has been with Feng Chia University at Taiwan as a Postdoctoral Researcher from July 2010 to June 2012. His research interests include image processing and multimedia security.