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Paper

A Serial Unequal Error Protection Code System Using Multilevel Trellis Coded Modulation with Ring-type Signal Constellations for AWGN Channels

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We propose a serial unequal error protection (UEP) code system for use with information sources that contain a mixture of both important and less important data. To achieve UEP, the proposed scheme uses a form of Trellis coded modulation (TCM) which encodes the data by switching between some codes that use different signal constellations. So we propose ring-type signal constellations with M levels of importance (MRING). Also, as no extra information about which code is used is added, the receiver estimates which code was used in the transmitter by examining the received signal points. In this paper, theoretical analyses of the 2RING signal constellations (that is, for $M = 2$) and TCM codes are presented, and the effectiveness and the validity of the system for additive white Gaussian noise (AWGN) channels are confirmed using theoretical analyses and computer simulations. © 2010 Institute of Electrical Engineers of Japan. Published by John Wiley & Sons, Inc.

Keywords: unequal error protection (UEP), two-ring signal constellations (2RING), Trellis coded modulation (TCM), additive white Gaussian noise (AWGN)

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1. Introduction

In certain communication systems, an information sequence may consist of several parts that have different degrees of significance and hence require different levels of protection against noise. Codes that are designed to provide different levels of data protection are known as unequal error protection (UEP) codes [1]. For example, in packet communications, the header must be protected more than the payload, because in the worst case, if the destination address is lost, the entire packet will be lost. Similarly, UEP is useful for protecting the unique word in a data frame transmission and the header information in asynchronous transfer mode (ATM) communication systems. Also, if we transfer images using a stronger error correcting code, the information bit rate is lower and the image quality is degraded. On the other hand, if we transfer images using a weaker error correcting code, the image quality is still degraded due to the influence of noise. In such a situation, applying UEP is useful. Only the part of the image that is of interest is strongly protected, and the other parts are weakly protected. Also, as an application of UEP, a digital satellite communication system using graceful coding has been considered [2,3]. In a graceful coding, we first classify transmitted data into some groups in terms of allocated bit error rate (BER). This results in giving each group UEP. Therefore, even if the signal-to-noise ratio (SNR) decreases, the received information need not be cut off suddenly, and we can communicate with gradually degraded quality for some groups by using UEP. Moreover, advanced research on UEP can be applied to adaptive coding techniques [4], which are realized by multiplexing codes with various error correcting capabilities. Also, not only academic studies but also practical developments [5] have been reported. Therefore, it is important to study UEP systems. Hereafter, high importance is denoted by 'H' and low importance is denoted by 'L'. For example, the low importance level is denoted by 'level-L', low importance data is denoted by 'data-L', and the high importance code is denoted by 'code-H'.

UEP codes were first studied by Masnick and Wolf [6] and later by several authors [7–18]. The details for the previous schemes will be described in Section 2. In this paper, we propose an improvement of the time-multiplexing approach mentioned in [8,9]. However, the proposed system is different from these schemes, as described below. In these schemes [8,9], it is assumed that the data stream is separated into two parallel data streams, consisting of data-H and data-L and periodic switching is needed. Since the serial data stream that we consider has a random mixture of important and less important data, periodic switching is not possible. This was motivated by our previous work on intelligent communication systems [19–21], where the transmitted data contains a mixture data-H and data-L. Therefore, we propose a scheme that switches between some codes of differing error protection capacity. In order to distinguish the codes, we use a different signal constellation for each code. This is equivalent to using the importance level to select the transmitted signal constellation. As the signal constellation, we propose the combination of two QPSK constellations of different energy, which we call RING-type constellations. This method does not require extra information, so it has the advantage of not reducing the information rate. However, in the receiver, the importance level that was used in the transmitter must be estimated. So, we develop an importance level estimation algorithm based on maximum likelihood detection (MLD). In this way, we can achieve UEP for serial data.

In previous research, we proposed 8-ASK-type, RING-type, and trapezoid-type signal constellations, and the effectiveness of the proposed UEP system for additive white Gaussian noise (AWGN) channels was shown [22]. Next, we proposed a finite impulse response (FIR) linear equalizer based on the normalized least mean square (LMS) algorithm [23,24] and a decision feedback equalizer (DFE) based on the recursive least squares (RLS) algorithm [25] as a frequency selective fading measure. As a result, we showed

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the effectiveness of the proposed UEP system. However, in these papers [22–25], we mainly presented simulation results and showed the implementation method for only two or three levels of importance.

In this paper, we describe the processing details of the proposed system, including the differences from previous schemes and extension to the general case with M levels of importance. Moreover, we theoretically analyze the proposed UEP system using the 2RING type constellations for AWGN channels. Finally, the validity of the theoretical analyses and the effectiveness of the proposed system are shown using computer simulations.

The rest of our paper is organized as follows. In Section 2, previous UEP schemes are described. In Section 3, we introduce our UEP scheme. In Section 4, we present theoretical analyses of our system. In Section 5, we present simulation results to show the performance of our system. Finally, we present our conclusions in Section 6.

2. Previous UEP Schemes

In this section, we describe typical multilevel encoders, methods using a nonuniform signal constellation and methods using coded modulation with time multiplexing as typical previously proposed UEP schemes as well as integrated and other technologies.

2.1. Multilevel encoder A typical multilevel encoder [7] is shown in Fig. 1. This method can be considered to be a UEP system since any error rate can be selected at each level. We mainly discuss coding to create the desired UEP characteristics in the transmitter. The source encoder divides the information sequence into P parallel sequences in decreasing order of importance. The encoding circuit consists of the P encoders with the error correcting codes $C_1, \ldots, C_P$ with rates $n_1, \ldots, n_P$ to create the desired UEP characteristics. The 2^P points in the signal constellation are labeled with numbers from 0 to $2^P - 1$. In Fig. 1, the signal selector chooses the signal point s from the code bits s_i using

$$s = \sum_{i=1}^{P} s_i 2^{i-1} \tag{1}$$

In general, although encoding is simple, the disadvantage of this multilevel encoder is that the decoding process is complex. For example, the multistage decoder introduced in [7]requires a large amount of computation.

2.2. Nonuniform signal constellation We describe a method to create the desired UEP characteristics using a nonuniform signal constellation. This is a method to obtain different bit error rates by modifying the signal constellation to increase the minimum squared Euclidean distance (MSED) in some bits while sacrificing the MSED in other bits. In Fig. 2, a uniform signal constellation, here QPSK, and a nonuniform signal constellation are shown. Points A, B, C, and D are uniform signal points and points A′, B′, C′, and D′ are nonuniform signal points. In Fig. 2, it is assumed that $d_2 < d < d_1$. When the data is transmitted using a nonuniform signal constellation, the distance d_1 is larger than the distance d_2, resulting in a lower error rate for the a_1 bit than the a_2 bit. Thus, the desired UEP characteristics are created. Naturally, the code rate is related to the UEP system's performance. This method is the basic principle of the non-set division method [14,15], which divides signal points using a method different from Ungerboeck's. However, this method is limited by the MSED of the original signal constellation, and can only be used with two importance levels. Moreover, the complexity of the signal constellation for schemes such as 16QAM with a large number of symbols is a problem.

2.3. Coded modulation with time multiplexing In general, multilevel encoders must send extra bits to achieve coding gain, which results in a loss in bandwidth efficiency. To correct this, methods using coded modulation with time multiplexing are used in [8,9]. An example of the latter for two importance levels is shown in Fig. 3 [8,9]. Information from the information source is classified as having either a level-L or a level-H, and then encoded using a code corresponding to the importance level. The data-H uses a more powerful code (Encoder-H), while the data-L uses a less powerful code (Encoder-L). In this system, the information source decides the importance level, and information is processed in parallel. In the system shown in Fig. 3, the outputs of Encoder-H and Encoder-L are mapped to signal points, so the following equation must be satisfied.

$$m_L + r_L = m_H + r_H \tag{2}$$

Here, m_L and m_H are the number of information bits to be encoded in the data-L and data-H streams, respectively, while r_L and r_H are the number of parity bits added by Encoder-L and Encoder-H, respectively. At the receiver, a decoder matched to each encoder decodes the received data.

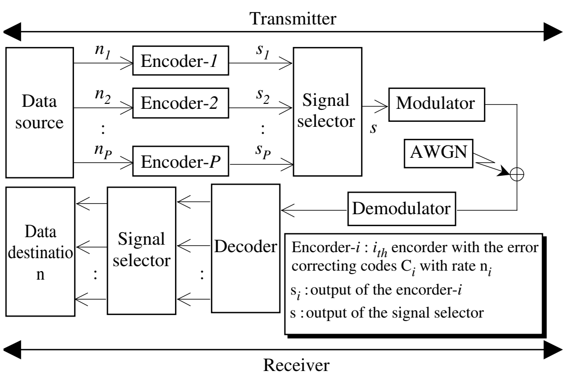

Fig. 1. Multilevel encoder [7]

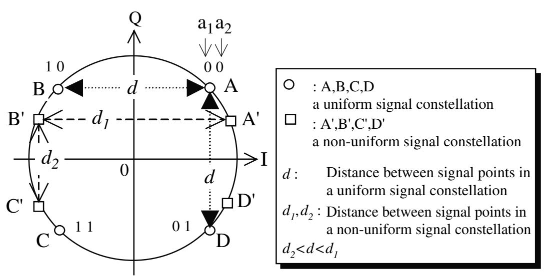

Fig. 2. Nonuniform signal constellation

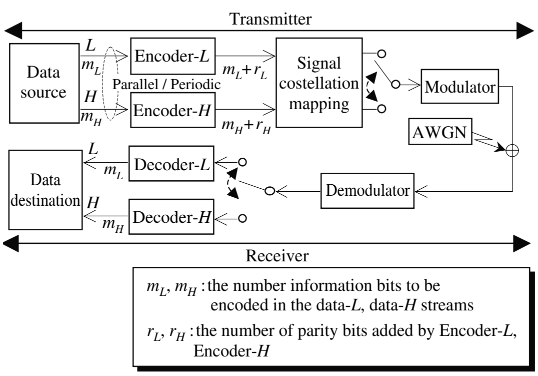

Fig. 3. Coded modulation with time multiplexing [8,9]

2.4. Integrated and other technologies Moreover, many approaches that integrate the technologies mentioned in Sections 2.1–2.3 and other technologies have been proposed [10–17]. For example, in [13,14] a method, which is different from Ungerboeck's method, of dividing signal points using a combination of multilevel encoders and nonuniform signal constellations is proposed and its effectiveness is shown. Recently, Turbo codes and low-density parity check (LDPC) codes [1], which are encoding technologies that approach the Shannon limit, have been given much attention. UEP with Turbo codes were studied in [16] and UEP with LDPC codes were studied in [17,18], and so on.

3. Proposed UEP Scheme

In this section, we describe the proposed UEP scheme. First, we show the proposed system model and describe details of the processing. Second, we show the proposed signal constellations that allow us to distinguish among importance levels. Next, we describe the importance level estimation algorithm that decides which signal constellation the received signal came from. Finally, we describe the system assumptions.

3.1. System model The proposed scheme is outlined in Fig. 4. This scheme uses two importance levels. This is an improvement over the time-multiplexing approach mentioned in previous schemes [8,9]. In these schemes, it is assumed that the data stream is separated into two parallel data streams, consisting of data-H and data-L, and periodic switching is needed. However, the serial data stream that we consider has a random mixture of important and less important data. So, the proposed scheme encodes the data by randomly switching between two codes which use different signal constellations, i.e. we use multilevel Trellis coding to realize UEP. No extra information about which code was used is added to denote importance. This method has the advantage of not reducing the information rate. As more important information should be more strongly protected from errors, it is allocated to a large ring. The opposite can be said about less important information. In the same way, we can construct a UEP system having in general M importance levels. We show this concept in Fig. 5. As shown in Fig. 4, when $M = 2$, that is, the number of the importance levels is two, importance level-1 shown in Fig. 5 is allocated to level-L shown in Fig. 4 and importance level-2 shown in Fig. 5 is allocated to level-H shown in Fig. 4. Naturally, the code rate is related to the UEP system's performance. Therefore, in the proposed scheme, the number of importance levels and the protection rate can be controlled by adding or deleting a ring whose size is different. So, this method

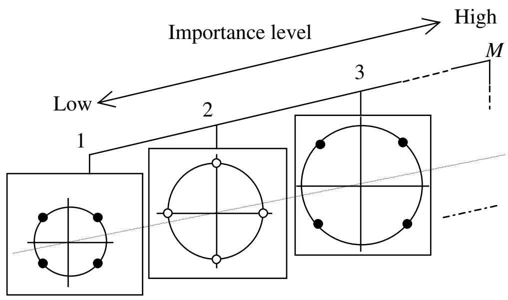

Fig. 5. Multilevel Trellis coding to realize UEP for M levels of importance

is simpler than methods using the nonuniform signal constellation described in Section 2.2 in terms of the modification of the number of importance levels and the protection rate.

In previous schemes [8,9], the information source decided the importance level. However, in the proposed system, the information source does not decide the importance level. Instead, the importance level is evaluated by the importance level decision block every N bits. That is, N is defined as the switching rate of the importance level and one frame consists of N bits. Also, information is processed serially by using switches.

In this way, we can achieve UEP systems for serial data. Moreover, in the proposed system, the same modulator is not shared by level-L and level-H. This removes the restriction of (2) required in the system shown in Fig. 3.

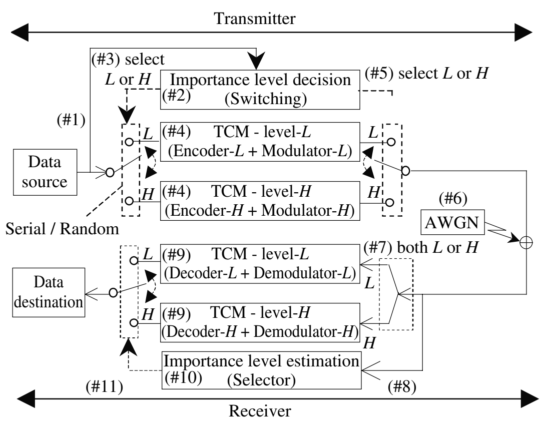

Fig. 4. The proposed UEP scheme in AWGN channels for two levels of importance

3.2. Processing details In this section, we describe the main processing steps used in the proposed scheme shown in Fig. 4 in detail. The numbers in the explanation, for example #1, correspond to the numbers in Fig. 4.

3.2.1. Transmitter In Steps 1–4, we describe the processing in the transmitter in Fig. 4.

Step 1. The input data comes from an information source which outputs random data∈{0,1}. Also, the input data is transmitted to the importance level decision block (#1).

Step 2. The importance level of the data is evaluated by the importance level decision block every N bits (#2). This decision controls the switch ahead. In this paper, in order to focus on the UEP implementation itself, we decide the importance level randomly. In Fig. 4, if the output of the importance level decision block is 'L', then the switches will be in the 'up' position. If the output is 'H', then the switches will be in the 'down' position (#3).

Step 3. We prepare codes that have different signal constellations according to the importance level. We describe this constellation in Section 3.3 Moreover, we combine coding and modulation using Trellis coded modulation (TCM) with four states [26] at the same time (#4). Information bits are allocated to signal points based on Gray coding. The distance between the signal points is larger for data-H, resulting in stronger error protection. Moreover, we encode the data differently according to the importance level to create UEP characteristics. The above-mentioned processing can be applied to the general case with M levels of importance.

Step 4. The data is selected by changing the switches according to the importance level decision performed in Step 2 every N bits (#5).

3.2.2. Receiver In Steps 5–7, we describe the processing in the receiver in Fig. 4.

Step 5. AWGN affects the transmitted signal in the channel (#6).

Step 6. The channel output is sent to all the decoders regardless of the importance (#7).

Step 7. Also, the data is transmitted into the importance level estimator (#8). In parallel with the decoding (#9), the encoder used in the transmitter, i.e. the importance level, is estimated every N bits using a importance level estimation algorithm based on maximum likelihood detection (MLD) (#10). Processing #9 and #10 is done in parallel to prevent throughput degradation. We describe this algorithm in Section 3.4. In this case, the encoder is either encoder-H or encoder-L. The output data is decided on the basis of the estimated result (#11). In this way, the receiver can determine the importance of the information.

3.3. Signal constellations In Section 3.2.1 Step 3, we stated that we use different signal constellations to change the importance level. The proposed signal constellations are called RING type and are shown in Fig. 6. Also, the proposed signal constellations correspond to the concept shown in Fig. 5. These signal constellations are the combination of some QPSK constellations of different energy. In order to separate the points as much as possible, the phase difference of each QPSK constellation is $\pi/4$. In Fig. 6, the constellations for M levels are shown, and they are called the MRING type constellations. This is equivalent to the superposition of one ring from each importance level 1 to M in Fig. 5. For example, the 2RING type constellations can support two importance levels: high and low. Data-H is assigned to the outer RING, and data-L to the inner RING. In Sections 4.1–4.4, we analyze the 2RING type constellations in detail. In previous works, such circular-signal constellations have been proposed. For example, a circular-signal constellation for 16APSK (amplitude PSK) was proposed [28,29], but it has not been applied to UEP systems. Moreover, the proposed RING-type constellations have not been used in previous UEP systems [5–18].

3.4. Importance level estimation algorithm As we mentioned in Section 3.2.2 Step 7, the receiver does not know which code was used to encode the data, so the performance of the entire UEP system depends heavily on the performance of the importance level estimation process. It is our goal to estimate which signal constellation, that is, which importance level, the received signal came from using the transmitted signal. Specifically, we propose an importance level estimation algorithm based on MLD [30].

Below, we describe our estimation algorithm separately for each step. This algorithm is applicable to M levels in general, that is, MRING type constellations. However, as an example, we describe the case for the 2RING type constellations shown in Fig. 7. We label the ith signal point for code-L l_i and the jth signal point for

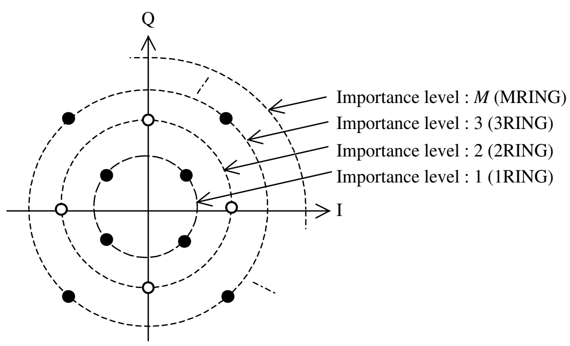

Fig. 6. RING-type constellations

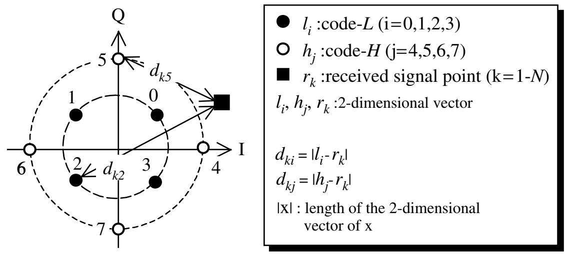

Fig. 7. Importance level estimation for 2RING type constellations

code-H h_j. However, i∈{0,1,2,3} and j∈{4,5,6,7}. Also, the l_i, h_j, r_k, and n_k are the two-dimensional vectors and $|\mathbf{x}|$ is the length of the two-dimensional vector $\mathbf{x}$. In this paper, since we are assuming AWGN channels, the received signal point r_k will be either $l_i + n_k$ or $h_j + n_k$, where n_k is a zero-mean Gaussian random variable with variance $N_0/2$. Here, N_0 is the power spectral density of the noise.

Step 1. We compute the distances d_{ki} and d_{kj} from the kth received signal to each signal point (code-L: l_i, code-H: h_j) as

$$d_{ki} = |l_i - r_k| \quad (3)$$

$$d_{kj} = |h_j - r_k| \quad (4)$$

In Fig. 7, the case for $i = 2$ (d_{k2}) and $j = 5$ (d_{k5}) is shown.

Step 2. We select the smallest of the distances computed in Step 1: $\min(d_{ki})$, $\min(d_{kj})$.

Step 3. In our UEP coding scheme, as either l_i or h_j will be sent N times in succession, we repeat the above Steps 1 and 2 N times and add the resulting smallest distances to obtain the total distance. Then, we form decision variables $\mu_{\rm L}$ and $\mu_{\rm H}$ for code-L and code-H, respectively as

$$\mu_{\rm L} = \frac{1}{N}\sum_{k=1}^{N} |\min(d_{ki})|^2 \quad (5)$$

$$\mu_{\rm H} = \frac{1}{N}\sum_{k=1}^{N} |\min(d_{kj})|^2 \quad (6)$$

Step 4. Finally, the next decisions are made.

If $\mu_{\rm L} < \mu_{\rm H}$, code-L is the currently used importance level.

If $\mu_{\rm L} > \mu_{\rm H}$, code-H is the currently used importance level. In other words, the point closest to the received signal is used as the reference point in the calculation of $\mu_{\rm L}$ and $\mu_{\rm H}$.

In this way, in the receiver and the importance level, that is, the code used in the transmitter, can be estimated from the received signal without extra information.

3.5. System assumptions Here, we describe the system assumptions.

(a) In this paper, to evaluate the UEP implementation itself, we do not consider the importance definition and methods to determine the importance level. We merely assume that the importance level has been decided and changes every N bits (1 frame) in the importance level decision block (see Section 3.2.1 Step 2).

(b) Since we want to evaluate the UEP properties of the proposed system, it is assumed that the frame synchronization of the receiver to the transmitter is ideal.

4. Theoretical Analyses

In this section, we present theoretical analyses of our system. The performance of the proposed UEP system depends on both the signal constellation and the codes used as the code-L and code-H. About the former, we examine the role of the signal constellation in Sections 4.1–4.4. About the latter, we examine the asymptotic coding gain to evaluate TCM codes for use in our proposed system in Section 4.5. In this paper, we first analyze the 2RING as an example of RING-type constellations.

4.1. Geometrical constraint An analysis model of 2RING type constellations is shown in Fig. 8. The distance between signal points in the code-L is d_L, while the distance between those in the code-H is d_H. The minimum distance between signals in the code-L and signals in the code-H is given by d_c. Since d_H is larger than d_L, we can write d_L in terms of d_H as

$$d_L = \beta d_H \tag{7}$$

where $0 < \beta < 1$. That is, β is the ring ratio of ring-L and ring-H. Now, in order to further parameterize the families so that d_c and d_H are related, we introduce γ such that

$$d_H = \gamma d_c \tag{8}$$

However, γ and β cannot be chosen independently, because changing one of the distances results in a change in the two other distances. For 2RING type constellations (see [26]),

$$\gamma^2 = \frac{2}{\beta^2 - \sqrt{2}\beta + 1} \tag{9}$$

The meaningful range of γ^2 is $2 < \gamma^2 < 3.414$.

4.2. Average energy Since each transmitted signal has a different energy, the average energy is used to calculate the SNR. In terms of the signal constellations, the energy of each signal is just the squared Euclidean distance of the signal point from the origin. We use equally probable signals, so each signal's energy is given the same weight in the calculation of the average energy. The average energy is defined as

$$\overline{E} = \frac{1}{K}\sum_{i=1}^{K} E_i \tag{10}$$

where E_i is the energy of the ith signal and K is the number of signals in the constellation. In terms of the signal constellation, E_i is just the squared Euclidean distance of the ith signal point from the origin. The 2RING type has an average energy given by

$$\overline{E} = \left[\frac{1+\beta^2}{2(\beta^2 - \sqrt{2}\beta + 1)}\right] d_c^2 \tag{11}$$

This expression is necessary for calculation of the asymptotic coding gain, i.e. (17).

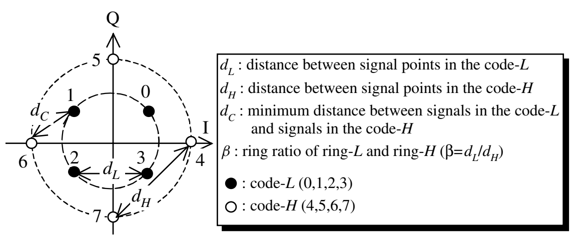

Fig. 8. Analysis model of 2RING type constellations

4.3. Importance level estimation error rate As we mentioned in Section 3.2.2 Step 7, in the receiver, it is necessary to estimate the encoder, that is, the importance level used in the transmitter, correctly. For example, for level-H, if encoder-H is used in the transmitter, we must estimate code-H in the receiver. The same can be said for level-L. The importance level estimation error rate is the probability that code-H is estimated incorrectly to be code-L or vice versa. We derive an approximate expression of the importance level estimation error rate for the 2RING type constellations in AWGN channels. Though in the 2RING type constellation the threshold between code-H and code-L is two dimensional, for simplification, a one-dimensional approximation is derived. It is given by (see [26])

$$P\left(x > \frac{d_c}{2}\right) = \sqrt{\frac{\pi - 2}{4\pi N}}\,\mathrm{erfc}\left[\sqrt{\frac{N d_c^2 \overline{E}}{4N_0}} - \sqrt{\frac{N}{\pi}}\right] \tag{12}$$

4.4. Relationship between the signal constellation and the error rate The error rate performance largely depends on the distances between signal points. Namely, the average bit error rate for each code (code-H or code-L) is related to the distance d_H or d_L and the importance level estimation error rate for the 2RING type constellations is related to the distance d_c. To evaluate the relationship between the signal constellation and the error rate, we introduce the following minimum squared Euclidean distances normalized by the average energy: $d_H^2/\overline{E}$, $d_L^2/\overline{E}$, $d_C^2/\overline{E}$. They are given by (13)–(15).

The average bit error rate for code-H:

$$\frac{d_H^2}{\overline{E}} = -\frac{4\beta^2}{1+\beta^2} + 4 \tag{13}$$

The average bit error rate for code-L:

$$\frac{d_L^2}{\overline{E}} = \frac{4\beta^2}{1+\beta^2} \tag{14}$$

The importance level estimation error rate:

$$\frac{d_C^2}{\overline{E}} = \frac{2(\beta^2 - \sqrt{2}\beta + 1)}{1+\beta^2} \tag{15}$$

In Fig. 9, $d_H^2/\overline{E}$(level-H) and $d_L^2/\overline{E}$(level-L) are shown versus $d_C^2/\overline{E}$ as a function of β for $0 < \beta < 1$. Also, in Fig. 9, the points corresponding to $\beta = 0$, 0.25, 0.5, 0.7071, and 1 are shown clearly using marks. Here, when $\beta = 0.7071$ in Fig. 8, the distance between code-L (signal 0) and code-L (signal 2) is equal to the distance d_H. Moreover, the values on the vertical axis in Fig. 9 larger than 2 correspond to $d_H^2/\overline{E}$(level-H), while values smaller than 2 correspond to $d_L^2/\overline{E}$(level-L). The average bit error rate for each code (code-H or code-L) is related to $d_H^2/\overline{E}$ or $d_L^2/\overline{E}$, and the importance level estimation error rate for the 2RING type constellations is related to $d_C^2/\overline{E}$. These error rates decrease as the distances increase.

From Fig. 9, if we use a smaller β, d_c is larger, so the importance level estimation error rate for the 2RING type constellations decreases. Also, d_H is larger and the average bit error rate for the code-H decreases. Similarly, d_L is smaller and the average bit error rate for the code-L increases. If we use a larger β, the opposite is true. Therefore, since the value of β is related to both the average bit error rate for each code and the importance level estimation error rate for the 2RING type constellations, a trade-off exists among them.

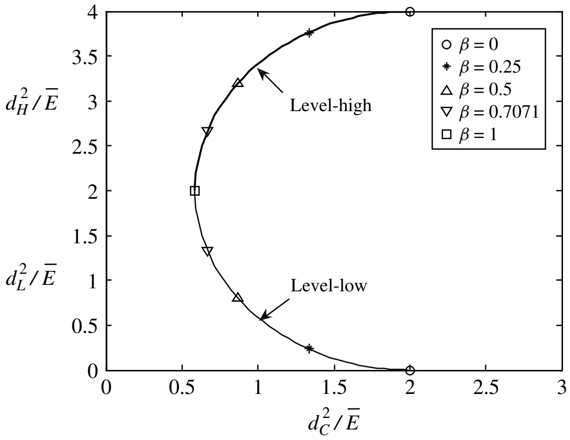

Fig. 9. $d_C^2/\overline{E}$ versus $d_H^2/\overline{E}$ (level-H), $d_L^2/\overline{E}$ (level-L) (The values on the vertical axis: $0 < d_L^2/\overline{E} < 2$, $2 < d_H^2/\overline{E} < 4$)

4.5. Asymptotic coding gain As we mentioned in Section 3.2.1 Step 3, in our proposed scheme we combine coding and modulation by using TCM. Using TCM, the data encoded by the convolutional code are allocated to signal points in accordance with the set partitioning method [1]. At the decoder, efficient error correction becomes possible by using the Viterbi decoding [1]. As a sample implementation of the proposed UEP system, we use the rate 1/2, four-state trellis code shown in Fig. 10 [26] for the code-H. In Fig. 10, the trellis branches are labeled with the input bit and the transmitted signal point in the code-H. For example, in state-S_0 if the input is '0', then the transmitted signal is '4'. By using this code, the minimum squared Euclidean distance corresponds to the difference between path A ($S_0 \to S_0 \to S_0 \to S_0$) and path B ($S_0 \to S_1 \to S_2 \to S_0$). For path A, the transmitted signal points are '4', '4', '4', and in path B, they are '6', '5', '6'. Therefore, the minimum squared Euclidean distance between path A and path B is given by

$$d_{\min}^2 = d^2(4,6) + d^2(4,5) + d^2(4,6) \tag{16}$$

where $d^2(i,j)$ is the squared Euclidean distance between signal i and signal j. Since the rate of the code-H is 1/2 and there are four points in the code-H signal sub-constellation, the information rate for the bits-H is 1.0 bit/T. To achieve less error protection for the bits-L, we do not use any coding. This also increases the information rate for the bits-L to 2.0 bits/T. Since we are considering the case when information-H and information-L occur with equal probability, the average information rate of the proposed UEP system is 1.5 bits/T. Using the UEP scheme, the coding gain for all constellations is achieved with an average information rate of 1.5 bits/T, while the coding gain of the uncoded-BPSK scheme is 1.0 bit/T. If the coding gain is adjusted to take this difference into account, the coding gain of the UEP scheme increases by 10 log(1.5/1.0) = 1.8 dB. Here, we examine the asymptotic coding gain G to examine the improvement of coding relative to an uncoded system. The asymptotic coding gain G of a code is given by

$$G = \frac{(d_{\min}^2/\overline{E})_{\text{coded}}}{(d_{\min}^2/\overline{E})_{\text{uncoded}}} \tag{17}$$

We use uncoded-BPSK as a reference. For uncoded-BPSK, the denominator of (17) is 4. The asymptotic coding gain of the data-H, G_{High}, is given by (18) after substituting (16) into (17). Otherwise, the asymptotic coding gain of the data-L, G_{Low}, is given by (19) because no coding is used.

$$G_{\text{High}} = 10 \log \left(\frac{5}{1+\beta^2} \right) [\text{dB}] \tag{18}$$

$$G_{\text{Low}} = 10 \log \left(\frac{\beta^2}{1+\beta^2} \right) [\text{dB}] \tag{19}$$

In Fig. 11, the asymptotic coding gains, G_{High} and G_{Low}, versus β for the 2RING type constellations are shown. From Fig. 11, the following fact can be obtained. Theoretically, the coding gain of the code-H is about 6.42 dB for $\beta = 0.5$, and about 5.71 dB for $\beta = 0.7071$. On the other hand, the coding loss of code-L is about 7.5 dB for $\beta = 0.5$, and about 5.0 dB for $\beta = 0.7071$. We examine this fact in Section 5.2-(c).

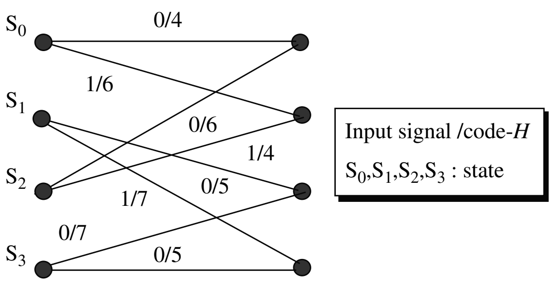

Fig. 10. Four-state Trellis code [27]

5. Performance Evaluation

In this section, we examine the performance of our system by using computer simulations. Moreover, we compare the results with the theoretical analyses described in Section 4. We assume AWGN channels. We use a rate 1/2 code for code-H and do not use coding for code-L. The information rate for the important bits is 1.0 bit/T, and for the less important bits is 2.0 bits/T. We also use the system assumptions described in Section 3.5. Also, we focus on the case when the important information and the less important information occur with equal probability. This can be generalized easily to the case when one importance level occurs more frequently than the other.

5.1. Importance level estimation error rate As we mentioned in Section 4.3, the importance level estimation error rate is the probability that code-H is estimated incorrectly to be code-L or vice versa. This value will be a factor showing whether code-L and code-H is distinguished correctly based on the proposed method. In Fig. 12, the importance level estimation error rate versus E_b/N_0 is shown. In Fig. 12, we show the next two performance results.

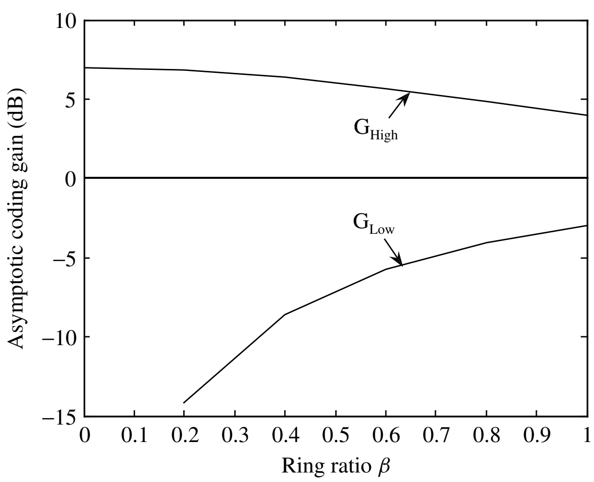

Fig. 11. Asymptotic coding gain versus β

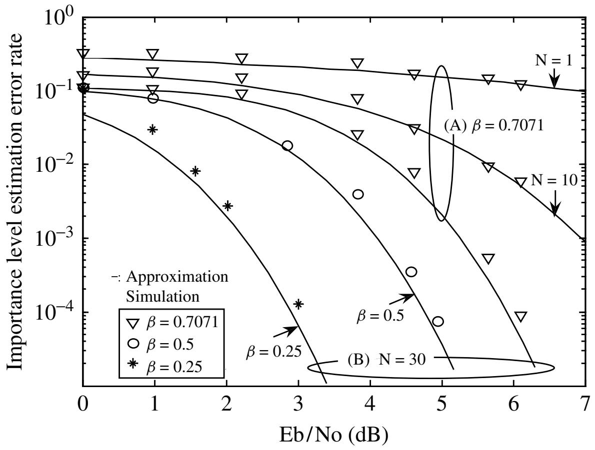

Fig. 12. Importance level estimation error rate versus E_b/N_0

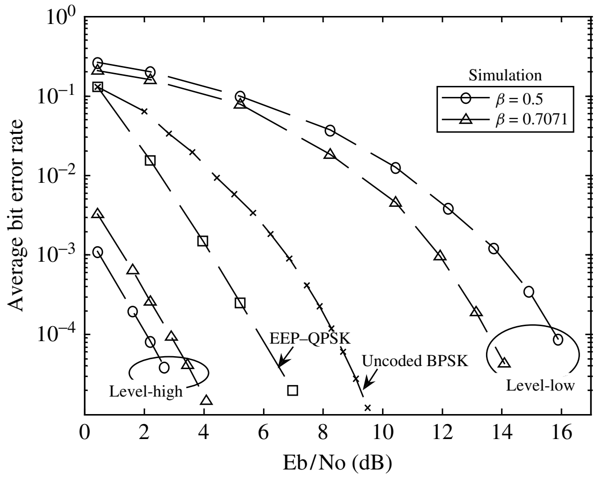

Fig. 13. Average bit error rate versus E_b/N_0 ($N = 30$)

(A) For a ring ratio of $\beta = 0.7071$, the performance when the importance level switching rate N is 1, 10, and 30.
(B) For a switching rate of $N = 30$, the performance when the ring ration β is 0.25, 0.5, and 0.7071.

Also, in Fig. 12, We show simulation results based on the algorithm described in Section 3.4, and the approximation given by (12) described in Section 4.3. The following conclusions can be drawn.

(a) Regardless of the value of the parameter β, the simulation results for the proposed algorithm roughly correspond to the approximation, which shows the validity of the derived approximate expression (12). The difference between the approximation and simulation values is due to the approximation used to derive (12).
(b) If the value of $\beta = 0.7071$ is constant, the performance also improves quickly as N is increased. This is due to the fact that if N is large, that is, the switching rate of the importance level is slow, importance level estimation errors are less likely to occur.
(c) We verify the theoretical analyses discussed in Section 4.4. As we mentioned in Section 4.4, $d_C^2/\overline{E}$ shown in Fig. 9 is related to the importance level estimation error rate for the 2RING type constellations. In Fig. 9, if we use a smaller β, $d_C^2/\overline{E}$ is larger, so the importance level estimation performance becomes better. In Fig. 12, if the value of $N = 30$ is constant, the performance for different values of β shows that as the signal points of code-L and code-H are made closer together, i.e. β is increased, the importance level estimation performance becomes worse. On the other hand, as the parameter β decreases, the importance level estimation error rate for the 2RING type constellations is improved. Therefore, the validity of the proposed method is shown.

5.2. Average bit error rate Since we want to focus only on the effect of the average bit error rate, in this evaluation we assume it is not affected by the code estimation error rate. In Fig. 13, the average bit error rate versus E_b/N_0 of the individual codes is shown. In Fig. 13, we show the performance for an importance level switching rate of $N = 30$ using the error estimation rate shown in Fig. 12. Also, as an example of the performance when β is varied, we use $\beta = 0.5$ and 0.7071. For comparison, the uncoded-BPSK and the proposed UEP schemes with equal error protection (EEP), i.e. QPSK combined with code-H, are shown. The following conclusions can be drawn.

(a) The error rate of the important information is lower than the error rate for an EEP scheme. For example, for code-H at an error rate of 10^{-4}, we get an improvement of about 3 dB for $\beta = 0.7071$ and about 4.17 dB for $\beta = 0.5$. On the other hand, for code-L at an error rate of 10^{-4}, we get a loss of about 8.0 dB for $\beta = 0.7071$ and about 10.66 dB for $\beta = 0.5$. In other words, we confirmed the creation of the desired UEP characteristics using the proposed method.
(b) We verify the theoretical analysis mentioned in Section 4.4. As we mentioned in Section 4.4, the average bit error rate for each code (code-L or code-H) is related to $d_L^2/\overline{E}$ or $d_H^2/\overline{E}$. From Fig. 9, $d_H^2/\overline{E}$ is larger and the average bit error rate performance for the code-H becomes better. Similarly, $d_L^2/\overline{E}$ is smaller and the average bit error rate performance for code-L becomes worse. From Fig. 13, we confirmed the following fact. When we compare the results for $\beta = 0.7174$ and $\beta = 0.5$, the average bit error rate performance for code-H is better when $\beta = 0.5$, but better for code-L when $\beta = 0.7174$. Therefore, the validity of the proposed method is shown.
(c) We verify the theoretical analysis mentioned in Section 4.5. To achieve an error rate of 10^{-4}, we get an improvement for code-H of about 6.0 dB for $\beta = 0.5$, and 5.25 dB for $\beta = 0.7071$ and a loss for code-L of about 7.55 dB for $\beta = 0.5$, and 5.25 dB for $\beta = 0.7071$. Here, compared to the results obtained in Section 4.5, the simulation results are a little inferior to the theoretical results. However, the simulation results roughly correspond to the theoretical results, so the validity of the proposed method was confirmed.

5.3. Overall evaluation of the proposed scheme
From the results of Sections 5.1-(c) and 5.2-(b), as we mentioned in Section 4.4, we confirmed the trade-off between the value of β, the average bit error rate for each code, and the importance level estimation error rate. In other words, the performance of the UEP code will depend on the three distances d_c, d_L, and d_H. The code separation distance d_c controls the importance level estimation performance, while d_L and d_H affect the codes performance of the code-L and code-H, respectively. Since these distances are related to one another, they cannot be independently varied. Therefore, a performance trade-off exists and it is necessary to choose the value of β that satisfies the requirements of the system. For example, when we want to protect data-H with a certain BER, first we calculate the difference between the SNR of uncoded-BPSK and

the SNR of data-H from Fig. 13. Next, a suitable value of β can be obtained from Fig. 11.

6. Conclusions

In this paper, we proposed an improvement of the time-multiplexing approach mentioned in [8,9]. In these schemes, it is assumed that the data stream is separated into two parallel data streams and periodic switching is needed. However, we proposed a scheme where the importance level is switched randomly between some codes of differing error protection capability. In order to distinguish the codes, we used a different signal constellation for each code. So, we proposed the combination of some QPSK constellations of different energy, which we call the RING-type signal constellations. In general, in order to implement UEP, extra information must be sent so that the original data can be reconstructed by the receiver in the correct order [7]. However, in the proposed system, as no extra information about which code is used is added, the receiver estimates which code was used in the transmitter by examining the received signal points, so it has the advantage of not reducing the information rate.

The effectiveness of the system for AWGN channels was shown using computer simulations. Moreover, the validity of the proposed method was confirmed from theoretical analyses and computer simulations. Our main conclusions are as follows.

(a) As for the average bit error rate for each code, the error rate of the important information is lower than the error rate for an equal error protection scheme. In other words, we confirmed the creation of the desired UEP characteristics using the proposed method.
(b) We theoretically calculated the asymptotic coding gain of the proposed system relative to the uncoded-BPSK. The simulation results roughly correspond to the theoretical results.
(c) As for the importance level estimation error rate, the simulation results for the proposed algorithm roughly corresponded to the approximation using the Gaussian approximation, and so the validity of both was confirmed.
(d) We theoretically showed the trade-off among the value of the ring ratio β, the average bit error rate for each code, and the importance level estimation error rate. Moreover, we confirmed this fact using computer simulations.

We are currently evaluating the performance by comparing the proposed scheme and other previous schemes and the performance for fading channels.

References

(1) Lin S, Costello D Jr. *Error Correcting Coding.* 2nd edn. Prentice Hall; 2004.
(2) Ramchandran K, Ortega A, Metin Uz K, Vetterli M. Multiresolution broadcast for digital HDTV using joint source/channel coding. *IEEE Journal on Selected Areas in Communications* 1993; **1(11)**:6–23.
(3) Dosch C. Digital broadcasting of studio-quality HDTV by satellite in the 21-GHz frequency range and by coaxial cable networks. *EBU Technical Review* 1993; **256**:47–53.
(4) Rice M, Wicker SB. Adaptive error control for slowly varying channels. *IEEE Transactions on Communications* 1994; **42(2/3/4)**: 917–926.
(5) Li H-B, Mitsugu O. Coded modulation equipment with unequal error protection. *Journal of the National Institute of Information and Communications Technology* 2003; **50(3/4)**:199–204.
(6) Masnick B, Wolf JK. On linear unequal error protection codes. *IEEE Transactions on Information Theory* 1967; **3**:600–607.
(7) Imai H, Hirakawa S. A new multilevel coding method using error correcting codes. *IEEE Transactions on Information Theory* 1977; **IT-23(3)**:371–377.
(8) Wei L-F. Coded modulation with unequal error protection. *IEEE Transactions on Communications* 1993; **41**:1439–1449.
(9) Calderbank AR, Seshadri N. Multilevel codes for un-equal error protection. *IEEE Transactions on Information Theory* 1993; **39**: 1234–1248.
(10) Boyarinov IM, Katsman GL. Linear unequal error pro-tection codes. *IEEE Transactions on Information Theory* 1981; **27**:168–175.
(11) van Gils WJ. Two topics on linear unequal error protection codes: bounds on their length and cyclic code classes. *IEEE Transactions on Information Theory* 1983; **29**:866–876.
(12) van Gils WJ. Linear unequal error protection codes from shorter codes. *IEEE Transactions on Information Theory* 1984; **30**:544–546.
(13) Lin MC, Lin CC, Lin S. Computer search for binary cyclic UEP codes of odd length up to 65. *IEEE Transactions on Information Theory* 1990; **36**:924–935.
(14) Morelos-Zaragoza R. Multilevel coded modulation for unequal error protection and multistage decoding—part I: symmetric constellations. *IEEE Transactions on Communications* 2000; **48(2)**:204–213.
(15) Isaka M. Multilevel coded modulation for unequal error protection and multistage decoding—part II: asymmetric constellations. *IEEE Transactions on Communications* 2000; **48(5)**:774–786.
(16) Shen C, Fitz MP. On the design of modern multilevel coded modulation for unequal error protection. *Proceedings of IEEE International Symposium on Communications (ICC2008)*, Beijing, China, 2008.
(17) Rahnavard N, Fekri F. Unequal error protection using low-density parity-check codes. *Proceedings IEEE International Symposium on Information Theory*, Chicago, IL, USA, 2004, 449.
(18) Rahnavard N, Fekri F. New result on unequal error protection using LDPC codes. *IEEE Communications Letters* 2006; **10(1)**:43–45.
(19) Suzuki N, Sasaki T, Kohno R, Imai H. An error controlling scheme according to the importance of individual segments of model based coded facial images. *IEICE Transactions Fundamentals* 1994; **E77-A**:1289–1297.
(20) Sasaki T, Kohno R, Imai H. An error controlling scheme based on different importance of segments of a natural language. *IEICE Transactions Fundamentals* 1992; **E75-A**:1076–1086.
(21) Sasaki T, Kohno R, Imai H. Variable error controlling schemes for intelligent error controlling systems. *IEICE Transactions Fundamentals* 1994; **E77-A**:1281–1288.
(22) Asano DK, Kohno R. Serial unequal error-protection codes based on trellis-coded modulation. *IEEE Transactions on Communications* 1997; **45**:633–636.
(23) Yamazaki S, Asano DK. A serial unequal error protection code system using trellis coded modulation and an adaptive equalizer for fading channels. *Proceedings of the 14th Asia-Pacific Conference on Communications*, Tokyo, Japan, 2008.
(24) Yamazaki S, Asano DK. An unequal error protection system using trellis coded modulation and an adaptive equalizer. *IEEJ Transactions on Electronics, Information and Systems* 2009; **129(1)**:147–148.
(25) Yamazaki S, Asano DK. A serial unequal error protection code system using a decision feedback equalizer for fading channels. *Proceedings of the 12th International Symposium on Wireless Personal Multimedia Communications*, Sendai, Japan, 2009.
(26) Yamazaki S, Asano DK. A serial unequal error protection code system using multilevel trellis coded modulation with two ring signal constellations for AWGN channels. *Proceedings of the 2009 International Symposium on Intelligent Signal Processing and Communication Systems*, Kanazawa, Japan, 2009, 315–318.
(27) Ungerboeck G. Channel coding with multilevel/phase signals. *IEEE Transactions on Information Theory* 1982; **IT-28**:55–67.
(28) Machida M, Handa S, Oshita S. Theoretical analysis of symbol error rates of (4,12) circular signal-set constellation for detection schemes. *IEICE Journal* 1999; **82-B(5)**:981–990.
(29) Chow YC, Nix AR, McGeehan JP. Analysis of 16-APSK modulation in AWGN and Rayleigh fading channel. *Electronics Letters* 1992; **28(17)**:1608–1610.
(30) Proakis JG. *Digital Communications.* Mc Graw-Hill; 1983; 700-702.

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