Comprehensive Analysis of Turbo TCM over Two Typical Channels

Zhiquan Bai, Dongfeng Yuan, and Kyungsup Kwak

Abstract: **In this paper, system performance of turbo trellis coded modulation (turbo TCM) is presented and analyzed through computer simulations over two typical channels, namely additive white Gaussian noise (AWGN) and Rayleigh fading channels. We use and compare different mapping strategies based on Ungerboeck partitioning (UP), block partitioning (BP), mixed partitioning (MP), Gray partitioning (GP), and Ungerboeck-Gray partitioning (UGP) of the signal constellation of the turbo TCM system. Furthermore, taking 8PSK modulation of turbo TCM as an example, our simulation results show that turbo TCM with UP can obtain better performance than turbo TCM with BP, MP, GP, and UGP in both AWGN and Rayleigh fading channels.**

Index Terms: **Mapping strategies, Rayleigh fading channel, turbo trellis coded modulation (turbo TCM).**

I. INTRODUCTION

It is well known that turbo codes, first proposed by C. Berrou *et al.* in 1993 [1], [2], can achieve good error-correcting performance. This code has many advantages: Flexible rate design (we can get this by using different puncturing schemes), different concatenation of recursive systematic convolutional (RSC) codes, etc. However, BPSK or QPSK modulation of the original turbo codes gives relatively low bandwidth efficiency.

In 1982, G. Ungerboeck proposed trellis coded modulation (TCM), which combines channel coding with modulation [3]. TCM lets us obtain higher bandwidth efficiency. Thus, combining turbo codes with TCM into turbo trellis coded modulation (turbo TCM), we can obtain good performance in both power and bandwidth efficiency. In this way, we can get better bit error rate (BER) with respect to traditional TCM and utilize the bandwidth more efficiently with respect to typical QPSK modulation of turbo codes. Turbo TCM [4], [5] has many advantages such as high rate, low bit-error rate, flexible rate design, etc.

TCM codes by themselves combine modulation and coding together by optimizing the Euclidean distance between codewords. They can be decoded by a symbol-by-symbol maximum a posteriori (MAP) algorithm. We will describe the structure, the basic idea and decoding algorithm of turbo TCM. Turbo TCM schemes with 8PSK modulation using five mapping strategies, Ungerboeck partitioning (UP), block partitioning (BP), mixed partitioning (MP), Gray partitioning (GP), and Ungerboeck-Gray partitioning (UGP) are presented. The performance over two typical channels, additive white Gaussian noise (AWGN) and Rayleigh fading channels, is evaluated through simulations, and the design principle of turbo TCM is discussed. It is noted that the mapping strategy is an inherent characteristic of turbo TCM, but there exist few metrics of selecting the mapping strategies of turbo TCM. In this paper, we study this metric and find the optimal mapping strategies.

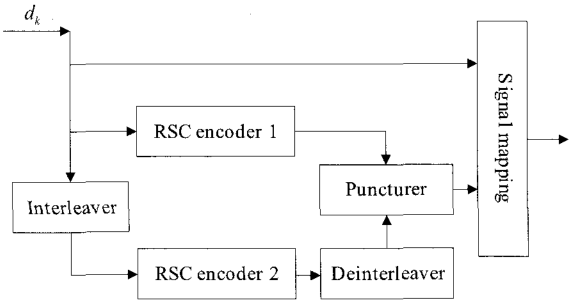

Fig. 1. Turbo TCM system.

The organization of this paper is as follows. In Section II, the turbo TCM system and the different mapping strategies are provided in detail. Section III presents the two typical channel models. Simulation results and performance analysis of turbo TCM with different mapping strategies are presented in Section IV. Finally, conclusions are presented in Section V.

II. TURBO TCM SYSTEM

This section describes the turbo TCM system model and the decoding algorithm of turbo TCM. Turbo TCM systems with 8PSK modulation utilizing five mapping strategies, UP, BP, MP, GP, and UGP, are presented. The design principle of turbo TCM is also discussed.

A. Turbo TCM Structure

The system diagram is shown in Fig. 1. At each time, information two-tuple d_k (here, we assume an RSC encoder with rate $\frac{2}{3}$) and its counterpart after interleaving are input to encoder1 and encoder 2, respectively. The output of encoder 2 is deinterleaved so that the two parity bits correspond to the same information bits. The puncturer here is used to improve the code rate of the system. The information bits and the check bit are mapped to a signal point in the modulation. In turbo TCM, we use the odd-even random interleaver first described in [6]. This maps even positions to even positions and odd positions to odd positions.

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Z. Bai and K. Kwak are with the INHA UWB-ITRC, Graduate School of Information Technology and Telecommunications, Inha University, Incheon, Korea, email: sdzqbai@hotmail.com, kskwak@inha.ac.kr.

D. Yuan is with the School of Information Science and Engineering, Shandong University, Jinan, Shandong, 250100,P. R. China, email: dfyuan@sdu.edu.cn.

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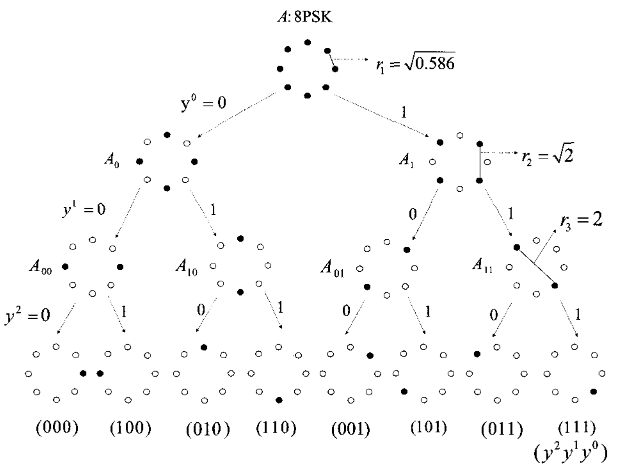

Fig. 2. Ungerboeck partitioning of 8PSK.

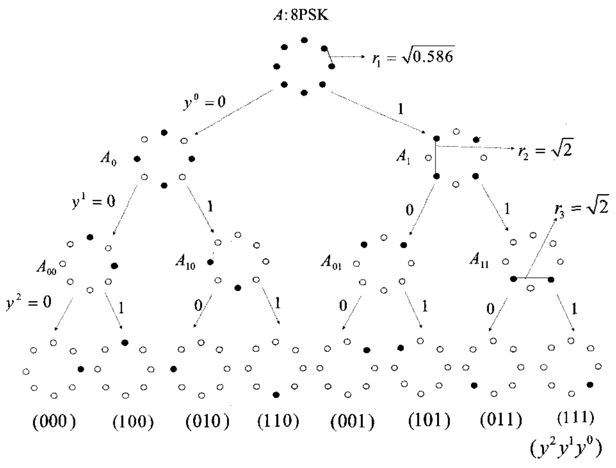

Fig. 4. Mixed partitioning of 8PSK.

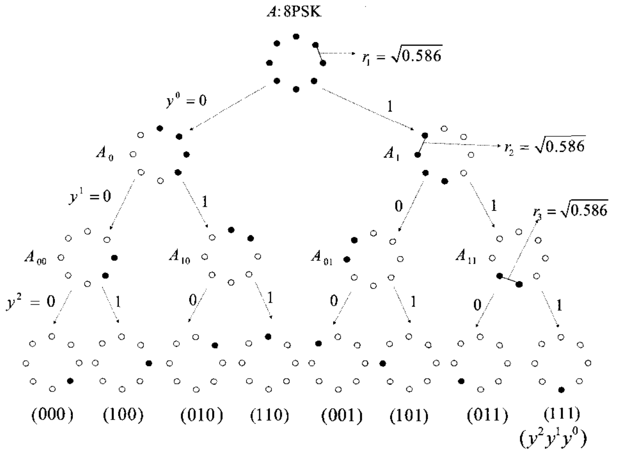

Fig. 3. Block partitioning of 8PSK.

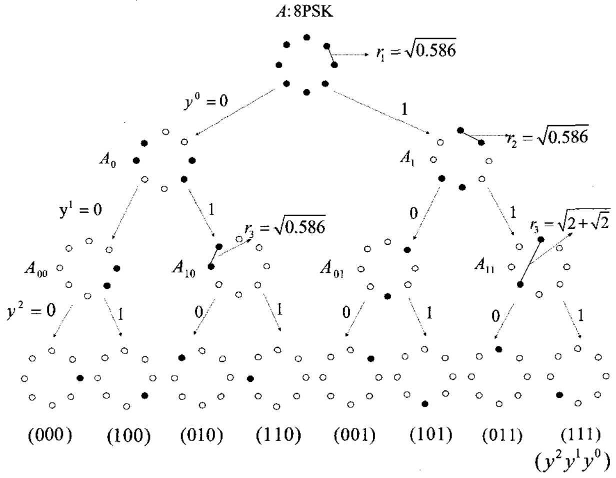

Fig. 5. Gray partitioning of 8PSK.

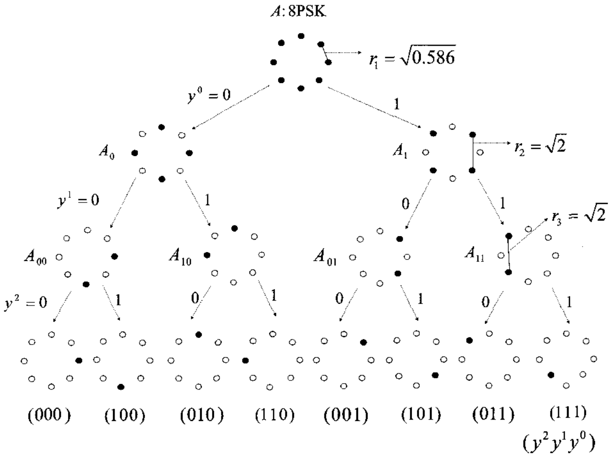

Fig. 6. Ungerboeck-Gray partitioning of 8PSK.

B. Mapping Strategies

Almost all coded modulation techniques [6] are based on symbol mapping through signal set partitioning introduced by Ungerboeck [3], [7].

Here, we use a set partitioning method proposed by Ungerboeck shown in Fig. 2. In this figure, $A_i (i = 0, 1, 00, \cdots, 11)$ denotes the signal subset with different set partitioning level and $y_i (i = 0, 1, 2)$ represents the code bit which is a component of a signal point. We can easily see that the minimum distances between the two signals in different subsets are $r_1 = \sqrt{0.586}$, $r_2 = \sqrt{2}$, and $r_3 = 2$. Distance parameters of subsets are greater than those before partitioning. This set partitioning is called UP.

Shown in Fig. 3 is another mapping strategy called BP [7]. Contrary to that in UP, its distance parameter in each level is unchanged, with $r_1 = r_2 = r_3 = \sqrt{0.586}$.

The third set partitioning method that is often used is MP [8]. This is shown in Fig. 4. We can change the turn of BP and UP to make different MP strategies when we use MP. The MP in Fig. 4 consists of UP-BP-UP; the first and the third partitionings are according to the UP rule, and the second partitioning is according to the BP rule. Another set partitioning method used to minimize the BER is GP [9]. We can see this method in Fig. 5. GP maximizes the number of adjacent pairs of signals that differ in only one bit. The last set partitioning we applied here is UGP as shown in Fig. 6. For this UGP, the Ungerboeck partitioning is used in the first set partitioning, then Gray partitioning is employed in the second partitioning. We should know that the code polynomials for the checked bits must be designed with the signal set to ensure the distance leaving and entering a state is $2r_2^2$. For an Ungerboeck mapping at the first level, the code polynomials must be of the form:

$$\begin{aligned} H^0(D) &= 1 + h_0^0 D + \cdots + h_0^{v-1} D^{v-1} + D^v \\ H^1(D) &= h_1^0 D + \cdots + h_1^{v-1} D^{v-1} + h_1^{v-1} D^v \\ &\vdots \\ H^m(D) &= h_m^0 D + \cdots + h_m^{v-1} D^{v-1} + h_m^v D^v \end{aligned} \tag{1}$$

where m is the number of the input bits. In the equations, h_i^v is the coefficient for the memory element D^v. Ungerboeck's rule states that $h_i^v = 0$ for $1 \le i \le m$ and $m \le v$ to ensure the desired distance properties.

In this work, we will discuss two conditions:

1. Keep the turbo TCM constituent encoder structure fixed for the different set partitioning;
2. design the corresponding turbo TCM constituent encoder structure according to the set partitioning.

For the 8PSK UP, we have the optimal turbo TCM encoder polynomials as $[h_2, h_1, h_0] = [0100, 0010, 1001]$ in binary notation. In the case of GP, we give the generation of encoder polynomials in detail. We assume that (y^2, y^1, y^0) represents the binary representation of an Ungerboeck partitioned 8PSK signal set. Let (z^2, z^1, z^0) be the binary representation of the other four signal sets. We can easily show that

$$\begin{aligned} &(z^2, z^1, z^0) = (y^0, y^1, y^2) \text{ for BP} \\ &(z^2, z^1, z^0) = (y^1, y^2, y^0) \text{ for MP} \\ &(z^2, z^1, z^0) = (y^2, y^2 + y^1, y^1 + y^0) \text{ for GP and} \\ &(z^2, z^1, z^0) = (y^2, y^2 + y^1, y^0) \text{ for UGP.} \end{aligned}$$

The parity check equation using polynomial notation [3] is

$$h^2(D)y^2(D) + h^1(D)y^1(D) + h^0(D)y^0(D) = 0 \tag{2}$$

where $h^0(D) = 1 + D^3$, $h^1(D) = D$, and $h^2(D) = D^2$. Dropping the (D) notation, we have $h^2y^2 + h^1y^1 + h^0y^0 = 0$.

For Gray mapping, we have

$$y^0 = z^0 + z^1 + z^2,\ y^1 = z^1 + z^2, \text{ and } y^2 = z^2 \tag{3}$$

where (y^2, y^1, y^0) is natural mapping and (z^2, z^1, z^0) is Gray mapping.

Thus, the parity check equation becomes

$$h^2z^2 + h^1(z^1 + z^2) + h^0(z^0 + z^1 + z^2) = 0 \tag{4}$$

$$(h^0 + h^1 + h^2)z^2 + (h^0 + h^1)z^1 + h^0z^0 = 0 \tag{5}$$

and

$$(1+D+D^2+D^3)z^2 + (1+D+D^3)z^1 + (1+D^3)z^0 = 0. \tag{6}$$

That is, the code polynomials should be $[1111, 1011, 1001]$ for GP. We have the other encoder generator polynomials as $[0010, 0100, 1001]$ for MP and $[0110, 0010, 1001]$ for UGP. For BP, the RSC encoder polynomial is $[1001, 0010, 0100]$. However, since the feedback polynomial does not contain a delay-free term, the encoder is not realizable in systematic form.

C. The Algorithm of the Decoder

We now introduce the decoding algorithm of turbo TCM based on the log-MAP algorithm [5], [11]. In turbo decoding of turbo TCM, the log-likelihood $L(d_k)$ of the information symbols is calculated as below, where $Y = (y_1, y_2, \cdots, y_N)$ is the received symbol

$$\begin{aligned} L(d_k = i) &= \log(p(d_k = i|Y)) \\ &= \log\left(K \sum_M \sum_{M'} \gamma_i(y_k, M', M)\alpha_{k-1}(M')\beta_k(M)\right) \end{aligned} \tag{7}$$

for $i = 0, 1, \cdots, 2^m - 1$ and a normalizing constant K. The final decision is expressed as $d_k = \arg\max_i L(d_k = i)$ where M, M' are the states of the trellis structure.

The terms γ_i, α_k, and β_k are defined as follows:

$$\begin{aligned} \gamma_i &= \gamma_i(y_k, M', M) \\ &= p(y_k|d_k = i, s_k = M, s_{k-1} = M') \\ &= p(s_k = M|d_k = i, s_{k-1} = M')p(d_k = i|s_{k-1} = M') \end{aligned} \tag{8}$$

$$\alpha_k = \alpha_k(M) = \sum_{M'} \sum_{i=0}^{2^m-1} \gamma_i(y_k, M', M)\alpha_{k-1}(M') \tag{9}$$

$$\beta_k = \beta_k(M) = \sum_{M'} \sum_{i=0}^{2^m-1} \gamma_i(y_{k+1}, M, M')\beta_{k+1}(M'). \tag{10}$$

We set the initial conditions below

$$\alpha_0(s) = \begin{cases} -1, & \text{if } s = 0 \\ 0, & \text{otherwise} \end{cases}$$

and

$$\beta_N(s) = \begin{cases} -1, & \text{if } s = 0 \\ 0, & \text{otherwise.} \end{cases}$$

In (8), we can let $p(d_k = i|s_{k-1} = M') = p(d_k = i)$. If there does not exist an i such that $p(s_k = M|d_k = 1, s_{k-1} = M') = 1$, then the term is set to zero.

In the decoding of binary turbo codes, we write the log-likelihood $L(d_k = i)$ of information bits in this form:

$$L(d_k = i) = L^i_{a\ priori} + L^i_{systematic} + L^i_{extrinsic}. \tag{11}$$

The three parts are the *a priori* component (the information given by the other decoder for the bit), the systematic component (corresponding to the received systematic value for the bit), and the extrinsic component (the part that depends on all other inputs). In the decoding of turbo TCM, we can write the output into two different components: i) *a priori* and ii) *e&s* (extrinsic and systematic), because the information bit and the check bit are mapped to a signal point together and the noise that affects the parity component also affects the systematic one. We write as

$$L(d_k = i) = L^i_{a\ priori} + L^i_{e\&s}. \tag{12}$$

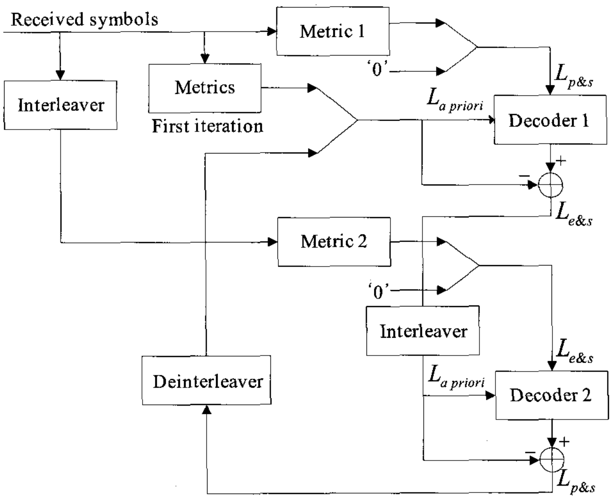

Fig. 7. The turbo TCM decoder structure.

We can calculate the extrinsic and systematic information as $L^i_{e\&s} = L(d_k = i) - L^i_{a\ priori}$. This term is transmitted to the other decoder as *a priori* information.

In the decoding process of turbo TCM, we should pay attention to the received symbols and the *a priori* information in the first decoding process since their initial value is different to latter iterations. In turbo TCM, each decoder alternately receives its corresponding encoder's noisy output symbols, and then the other encoder's noisy output symbols. Care is taken not to use the systematic information more than once in each decoder. We know that we must have the *a priori* information before the first decoding process. As seen in Fig. 7, the Metrics box calculates the *a priori* information $L^i_{a\ priori}$. If the symbol does not correspond to its own encoder, we determinate the *a priori* information as below [5].

$$\begin{aligned} L_{apriori} &= \log(p(d_k = i)) \\ &\approx \log(p(d_k = i|y_k)) = \log(C \times p(y_k|d_k = i)) \\ &= \log\left(\frac{C}{2} \times \sum_{j=0}^{1} p(y_k|d_k = i, b_k = j)\right) \end{aligned} \quad (13)$$

where C is a constant and $b_k \in \{0, 1\}$ is the parity bit. If the symbol corresponds to its own encoder, we set in the first iteration. The Metric 1 and Metric 2 boxes calculate $L^i_{p\&s}$, the parity and systematic log-likelihood. If the symbol from the corresponding encoder was transmitted, we set

$$L^i_{p\&s} = \log\left(p(y_k|d_k = i, s_k = M, s_{k-1} = M')\right). \quad (14)$$

If the symbol from the corresponding encoder was not transmitted, we set $L^i_{p\&s} = 0$. This term is one of the components of the transition probability .

III. TWO TYPICAL CHANNEL MODELS

A. AWGN Channel Model

The AWGN channel is the most common and simplest channel. The parameters of this channel obey the Gaussian distribution. Here, $n(t)$ is a sample function of the Gaussian process with double-sided power spectral density $N_0/2$. We assume that it is independent of the signal. The values of the mean and variance are zero and $N_0/2$, respectively.

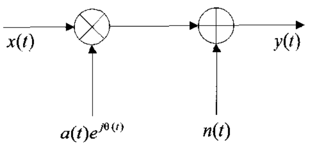

Fig. 8. Rayleigh fading channel model.

B. Rayleigh Fading Channel Model

Fig. 8 shows the model for the fading channel with additive white Gaussian noise. For slow fading processes, the channel gain can be considered constant over the symbol duration T_s. Throughout this work we consider a fully interleaved Rayleigh slow fading channel. 8PSK signaling with coherent detection is assumed. The discrete representation of the model is

$$y_k = ax_k + n_k \quad (15)$$

where x_k is an 8PSK complex symbol and n_k is a complex additive white Gaussian noise component with zero mean and variance $N_0/2$. The fading coefficient a is a random variable with probability density function: $f(a) = 2ae^{-a^2}$ for $a > 0$ and $E[a^2] = 1$. Perfect phase knowledge is assumed.

Knowledge of the channel gain at the receiver will be referred to as channel side information (CSI). CSI may be gained through the use of an auxiliary channel or a direct examination of the SNR. At the receiver, in order to simplify the complexity, we use the average value of CSI with $E[a] = 0.8862$.

IV. SIMULATION RESULTS

In our computer simulation, we performed a code search for an 8-state systematic convolutional encoder. We found that the performance of the encoder structure to be the same as the one that Robertson and Woerz presented [5]. This obtained the best performance for UP compared with other turbo TCM encoder structures. We will study the same 8-state turbo TCM encoder structure used in [5].

The turbo TCM with the optimal RSC encoder is [0100, 0010, 1001] for UP. The first two columns are the forward polynomials and the last column is the feedback polynomial, which is shown in Fig. 9. The rest of the turbo TCM encoder was already shown in Fig. 1. The bandwidth efficiency of the system is 2 bit/s/Hz, which is higher than traditional rate $1/2$ binary turbo codes whose bandwidth efficiency is 1 bit/s/Hz with QPSK (bit/s/Hz means bits per second per Hertz). This improves the bandwidth efficiency by two times. The interleaver we used is an odd-even random interleaver with the interleaver size being 1024.

A. Keep the Turbo TCM Encoder Fixed

When the iteration number is eight, we show the simulation results of different mapping strategies for an AWGN channel in Fig. 10. We can get better performance by using turbo TCM with

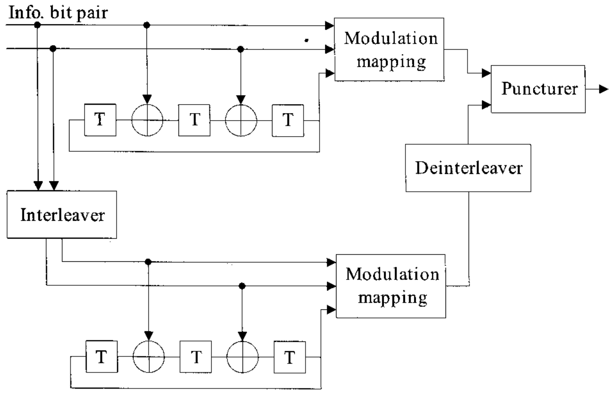

Fig. 9. Encoder structure of turbo TCM for UP.

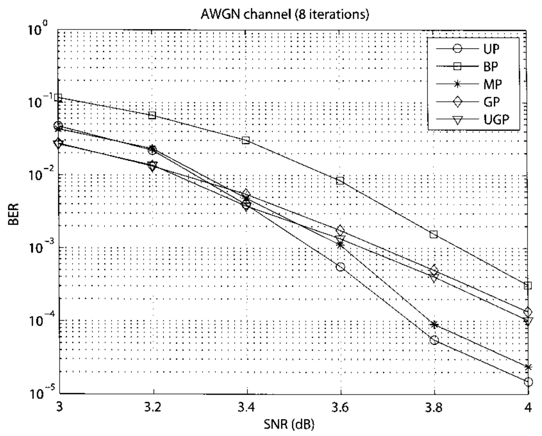

Fig. 10. Turbo TCM 8PSK with different mapping strategies in AWGN channel.

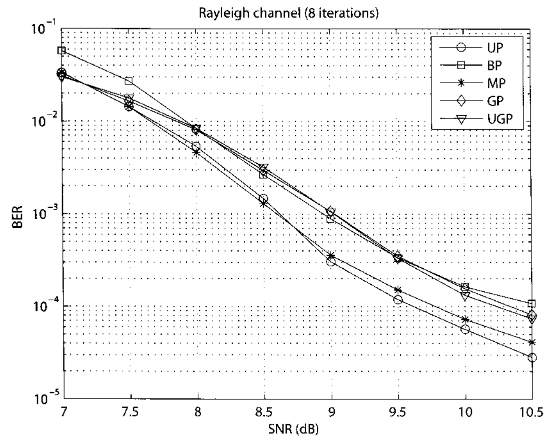

Fig. 11. Turbo TCM 8PSK with different mapping strategies in Rayleigh channel.

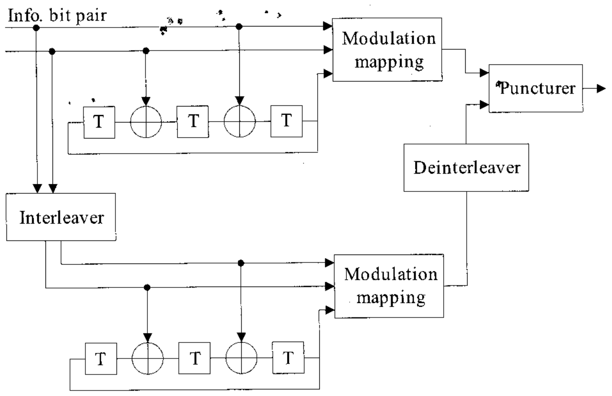

Fig. 12. Encoder structure of turbo TCM for MP.

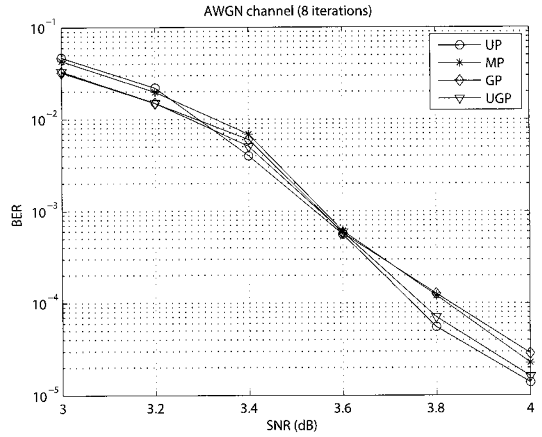

Fig. 13. Turbo TCM 8PSK with different mapping strategies in AWGN channel.

the UP strategy compared with other mapping strategies. When the BER is 10^{-3}, the E_b/N_0 we need is 3.86 dB, 3.63 dB, 3.68 dB, and 3.65 dB under BP, MP, GP, and UGP, respectively, but under UP the E_b/N_0 is just 3.54 dB. We conclude that using turbo TCM with UP we can have about 0.32 dB, 0.09 dB, 0.14 dB, and 0.12 dB gain compared with BP, MP, GP, and UGP, respectively, with eight iterations in an AWGN channel.

In the flat Rayleigh fading channel, we have the same conclusions as those for the AWGN channel. We show the BER performance of data transmission with the number of iterations being eight in Fig. 11. When the BER is around 10^{-4}, the E_b/N_0 we need is 9.60 dB, 10.60 dB, 9.80 dB, 10.35 dB, and 10.25 dB under UP, BP, MP, GP, and UGP, respectively. We conclude that using turbo TCM with UP, we have 1.0 dB, 0.20 dB, 0.75 dB, and 0.65 dB gain compared with BP, MP, GP, and UGP, respectively.

B. Design the Turbo TCM Encoder according to the Set Partitioning

In this part, we consider the redesigned turbo TCM encoder according to the set partitioning. As an example, the co-designed turbo TCM encoder structure under MP is shown in Fig. 12. In the case of BP, the co-designed encoder can not be realized. When the number of iterations is eight, the simulation results for an AWGN channel are shown in Fig. 13. When the BER is 10^{-4}, the E_b/N_0 we need is 3.83 dB, 3.84 dB, and 3.77 dB under MP, GP, and UGP, respectively, but under UP the E_b/N_0 is just 3.75 dB. We conclude that using turbo TCM with UP we can have about 0.08 dB, 0.09 dB, and 0.02 dB gain compared with MP, GP, and UGP, respectively, with eight iterations in an

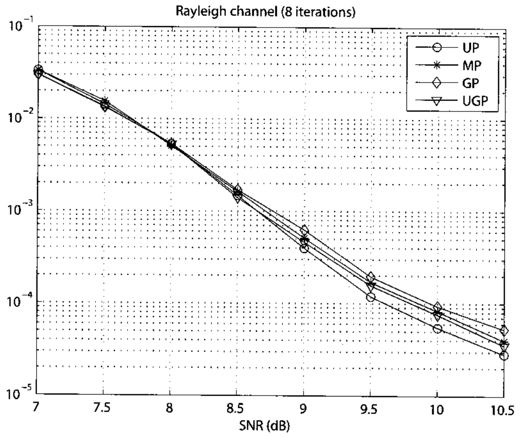

Fig. 14. Turbo TCM 8PSK with different mapping strategies in Rayleigh channel.

AWGN channel.

When the number of iterations is eight, we also show the BER curves of data transmission in the flat Rayleigh fading channel in Fig. 14. When the BER is around 10^{-4}, the E_b/N_0 we need is 9.60 dB, 9.90 dB, 10.00 dB, and 9.85 dB under UP, MP, GP, and UGP, respectively. We conclude that using turbo TCM with UP, we have 0.30 dB, 0.40 dB, and 0.25 dB gain compared with MP, GP, and UGP, respectively.

V. CONCLUSION

From our simulation results, we see that turbo TCM has good error correcting performance in the regions of low signal to noise ratio. We can get higher bandwidth efficiency by using turbo TCM, compared with binary turbo codes. When using turbo TCM with a code designed for UP, we get better BER performance with UP than turbo TCM with BP, MP, GP, and UGP. Under the co-designed scheme, we can no longer use BP (the encoder is not realizable) and the other schemes with different mapping strategies have almost the same performance. For the practically limited number of simulated transmissions and actual simulation conditions, there exist some differences among these schemes. The simulation results also reflect that under the practically simulated conditions, UP can have the best performance.

We know that the Euclidean distance is the metric for AWGN channels. From this point the Euclidean distance can be one of the metrics to evaluate the error-correcting performance. Based on our pervious work [13], [14], it is shown that turbo TCM can be used for mobile multimedia transmission with good BER performance.

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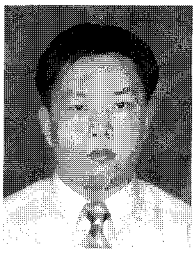
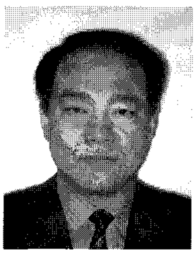
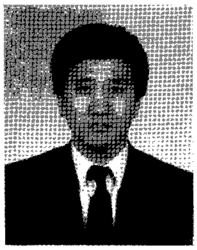


Zhiquan Bai was born in Baotou, Inner Mongolia, China in Jan. 1978. He received the B.S.degree from Department of Electronic Engineering, Inner Mongolia University, China in 2000, and M.S. degree from School of Information Science and Engineering, Shandong University, China in 2003, respectively. He now is pursuing his Ph.D. degree in the Graduate School of Information Technology and Telecommunications, Inha University, Korea. His current research fields include: Advanced channel coding (turbo codes), high efficient modulation schemes (turbo TCM), multimedia transmission, performance analysis of ultra wideband (UWB) communication system, *M*-ary modulation schemes of UWB system, and coded UWB system.



Dongfeng Yuan received his M.S. degree from Department of Electrical Engineering, Shandong University, China in 1988 and got his Ph.D. degree from Department of Electrical Engineering, Tsinghua University, China in Jan. 2000. Currently, he is a full professor and dean in School of Information Science and Engineering, Shandong University, China. He is a senior member of IEEE, a senior member of China Institute of Communications and China Institute of Electronics. From 1993–1994, he was a visiting professor in Electrical and Computer Department in the University of Calgary, Alberta, Canada, a visiting professor in Department of Electrical Engineering in the University of Erlangen, Germany, 1998–1999, a visiting professor in Department of Electrical Engineering and Computer Science in the University of Michigan, Ann Arbor, USA, 2001–2002. He has published over 200 papers in some technical journals and international conferences in his research field recent years. His research interests include: Multilevel coding and multistage decoding, space-time coded modulation, turbo codes, LDPC codes, OFDM techniques for high speed transmission in 4G, cross layer design, and unequal error protection characteristics in multimedia transmission in fading channels.



Kyungsup Kwak received the B.S. degree from the Inha University, Incheon, Korea in 1977, and the M.S. degree from the University of Southern California in 1981 and the Ph.D. degree from the University of California at San Diego in 1988, under the Inha University Fellowship and the Korea Electric Association Abroad Scholarship Grants, respectively. From 1988 to 1989, he was a member of Technical Staff at Hughes Network Systems, San Diego, California. From 1989 to 1990, he was with the IBM Network Analysis Center at Research Triangle Park, North Carolina. Since then he has been with the School of Information and Communication, Inha University, Korea as a professor. He had been the chairman of the School of Electrical and Computer Engineering from 1999 to 2000 and the dean of the Graduate School of Information Technology and Telecommunications from 2001 to 2002 at the Inha University, Inchon, Korea. He is the current directors of Advanced IT Research Center of Inha University, and UWB Wireless Communications Research Center, a key government IT research center, Korea. Since 1994, he had been serving as a member of Board of Directors, and during the term of 2000–2002 year, he had been the vice president for Korean Institute of Communication Sciences (KICS). He has been elected for the KISC's president of 2006 year term. In 1993, he received Engineering College Young Investigator Achievement Award from Inha University, and a distinguished service medal from the Institute of Electronics Engineers of Korea (IEEK). In 1996 and 1999, he received distinguished service medals from the KICS. He received the Inha University Engineering Paper Award and the LG Paper Award in 1998, and Motorola Paper Award in 2000. His research interests include multiple access communication systems, mobile communication systems, UWB radio systems and wireless sensor networks. Mr. Kwak is a member of IEEE, IEICE, KICS, and KIEE.