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A novel optimized constellation mapping scheme of the 16QAM for the BICM-ID in optical communication systems

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ABSTRACT

Considering the limited performance of the traditional Gray mapping at medium-to-high signal noise ratio (SNR) region, a novel constellation mapping scheme of 16 quadrature amplitude modulation (QAM) is proposed by redistributing bit position in order to optimize performance at medium-to-high SNR region for Bit-interleaved coded modulation with iterative decoding (BICM-ID) system. The novel mapping scheme can raise the unequal degree of the protection. And then the experiments based on the criterion of the mutual information analysis are performed. The channel capacity in BICM-ID system is comparatively analyzed with several previous constellation mapping schemes, the simulation results show that the channel capacity of the novel mapping scheme is 1.58 bit/channel-use more than that of the Gray mapping scheme at medium-to-high SNR region. Furthermore, combined with the low-density parity-check (LDPC) code, the novel mapping scheme with the assistance of the extrinsic information transfer (EXIT) charts in optical communication systems also displays the promising performance.

1. Introduction

The bit-interleaved coded modulation (BICM) is well applied in the third generation mobile communication system [1]. However, the use of the bit-interleavers brings about the decrease of free Euclidean distance, thus leading to performance reduction. To improve this drawback, one method of iterative decoding was proposed. The performance of BICM can be greatly improved through iterative information exchange between the demapper and the decoder, which can even approach the performance of Turbo-Trellis Coded Modulation (T-TCM) over Additive White Gaussian Noise (AWGN) channel in the case of low complexity. This modified BICM system, firstly introduced by Li Xiaodong [2,3], is usually referred to as BICM with iterative decoding (BICM-ID), which has been utilized in mobile communication system [4] and optical communication systems [5]. Recent trend in both academia and industry community is toward pushing the capacity [6,7] and information rate higher. It was recognized that the choice of symbol mapping is the crucial parameter to achieve a high coding gain over the iterations. With its growing international attention in academic circles, several mappings typically represented by Gray mapping for BICM-ID were presented [8,9]. At the same time, with the rapid growth of the capacity demand for optical transport networks, the various high-order digital modulations for high-speed optical communication systems have been proposed to obtain the higher spectral efficiency and the optical transmission experiment using the 8 quadrature amplitude modulation (QAM) modulation format with 114 Gb/s single channel rate has realized in document [10]. The 16QAM is one of the spectrum efficient transmission technologies [11,12]. Error control coding based on capacity-approaching channel codes for optical communication systems has received significant attention and research interest [12].

A novel scheme of constellation mapping of the 16QAM for BICM-ID is presented in order to compensate the disadvantages that Gray mapping scheme obtains the limited performance at medium-to-high signal noise ratio (SNR) region in this paper. Furthermore, several mapping schemes to search the optimal design scheme based on the mutual information and channel capacity are deeply investigated. The aim is to bring the more capacity-approaching coded modulation scheme for high-speed optical communication systems.

2. BICM-ID systems

2.1. The system model with the LDPC encoder

The schematic of the whole system is shown in Fig. 1. The transmitted source information sequences are primarily encoded as sequence u by the LDPC encoder. Then the encoded sequence

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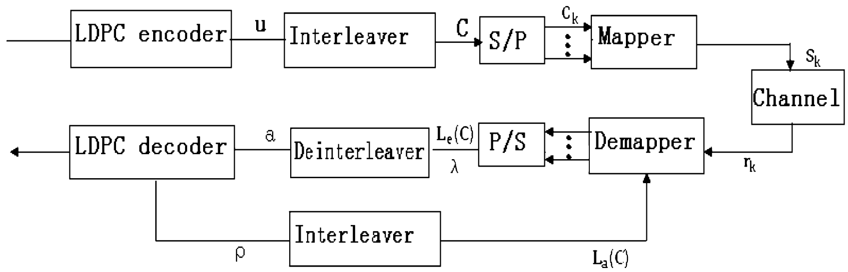

Fig. 1. LDPC-BICM-ID system model.

u is bit-interleaved to form the sequence C, which is afterwards transformed into the m subsequences through the serial-parallel conversion. Each subsequence C_k is mapped to a complex symbol S_k after entering the modulator in parallel.

At the receiver, the demapper processes the received symbols $r_k = a_k * S_k + n_k$, where a_k denotes the fading coefficient, and n_k is the complex zero-mean Gaussian noise with variance $\sigma_n^2 = N_0/2E_s$. The received symbol r_k are processed for the bit sequence λ, then the sequence λ are deinterleaved as the priori information a for the decoder. Hereafter, the posteriori information ρ is obtained through the decoding. Let the posteriori information ρ as the feedback priori information for the demodulator after re-interleaving, the iterations can be continued till the end of the decoding.

By calculating the related amount of the information, it is obviously to see the significant impact that the mapping scheme brings about for the performance of the overall system.

For the received symbol r_k, the corresponding priori loglikelihood ratios (LLR) of the coded bits is expressed as

$$L_a(c_k(i)) = \log\left(\frac{P(c_k(i)=0)}{P(c_k(i)=1)}\right) \tag{1}$$

And the output extrinsic LLRs is

$$L_e(c_k(i)) = \log\frac{P(c_k(i)=0|r_k, L_a(c_k))}{P(c_k(i)=1|r_k, L_a(c_k))} - L_a(c_k(i)) \tag{2}$$

2.2. Capacity limit for AWGN channel

From the research of relevant literature, optimal mapping can be obtained by analyzing the capacity of BICM system. Caire et al. [13] also derived an expression for the channel capacity limit C in document, which is as follows:

$$C = m - \sum_{i=1}^{m} E_{c,y}\left[\log_2\frac{\sum_{s\in S} p(y|s)}{\sum_{s\in S_{i,c_i}} p(y|s)}\right] \tag{3}$$

where $c = \{c_1, c_2, \ldots, c_m\} \in \{0, 1\}^m$, which is a set of m bits at the modulator input; y denotes the received signal, and $E_{c,y}$ denotes expectation with respect to c and y; S_{i,C_i} is the subset of all the signals $s \in S$ whose labels have the value $c_i \in \{0, 1\}$ in position ith.

Assuming an AWGN channel and making some minor modifications, we get

$$C = E_{c,y}\left[m - \log_2\frac{\left(\sum_{s\in S}\exp(-(d_{y,s}^2/\sigma^2))\right)^m}{\prod_{i-1}^{m}\sum_{s\in S_{i,c_i}}\exp(-(d_{y,s}^2/\sigma^2))}\right] \tag{4}$$

where $d_{y,s}$ is the Euclidean distance between signals y and s, the calculated capacity here is expressed in information bits per channel use (bit/channel-use).

2.3. EXIT-based techniques

The extrinsic information transfer (EXIT) analysis may be applied to design LDPC codes degree distribution which optimized decoding performance [14]. Its design goal turns out to match mutual information transfer characteristics of LDPC decoders through selection of variable node degrees (VND). Naturally there are the corresponding check node degrees (CND).

First step of generating VND transfer characteristics is to compute the mutual information at the input and output of the detector $I_{E,DET}(I_A, E_s/N_0)$, where I_A denotes the mutual information of a-prior LLRs at the detector. Thus the extrinsic information at the output of the variable node decoder is

$$\begin{aligned} &I_{E,VND}(I_A, d_v, E_s/N_0) \\ &= J\left(\sqrt{(d_v-1)[J^{-1}(I_A)^2] + [J^{-1}(I_{E,DET}(I_A, E_s/N_0))]^2}\right) \end{aligned} \tag{5}$$

where d_v refers to the variable node degree; J function computing the mutual information $I(X, \Lambda(Y))$; $Y = X + N$ is an AWGN channel where X is drawn from a QAM constellation, and $\Lambda(Y)$ is the LLR of the channel output.

Furthermore, the extrinsic information at the output of the CND can be computed in the same way

$$I_{E,CND}(I_A, d_c) = 1 - J\left(\sqrt{d_c-1}\cdot J^{-1}(1-I_A)\right) \tag{6}$$

where d_c represents the CND.

As in our system model the LDPC code is a part of the BICM-ID system, we can construct the EXIT curve of the LDPC decoder [15], which is a relationship between mutual information at the demapper output as priori mutual information for the LDPC decoder and the output extrinsic mutual information of the LDPC decoder. For this reason, we can optimize the system by matching between mapping schemes and LDPC codes, i.e., fitting the EXIT curves each other and minimizing the area within the EXIT chart's open tunnel.

3. Design criterion of the constellation mapping

Based on pairwise error probability, Caire et al. [13] innovatively deduced the progressive performance limit of BICM in Rayleigh fading channel. He pointed out that the minimum harmonic mean squared Euclidean distance (HMMSE) is the critical factor which impacts error probability. Since then HMMSE stated to become an important indicator to measure optimal constellation mapping.

Many studies on the mapping scheme based on the basis of Caire's research results has been performed, there are mainly two directions, one is based on Euclidean distance and another is based on channel capacity.

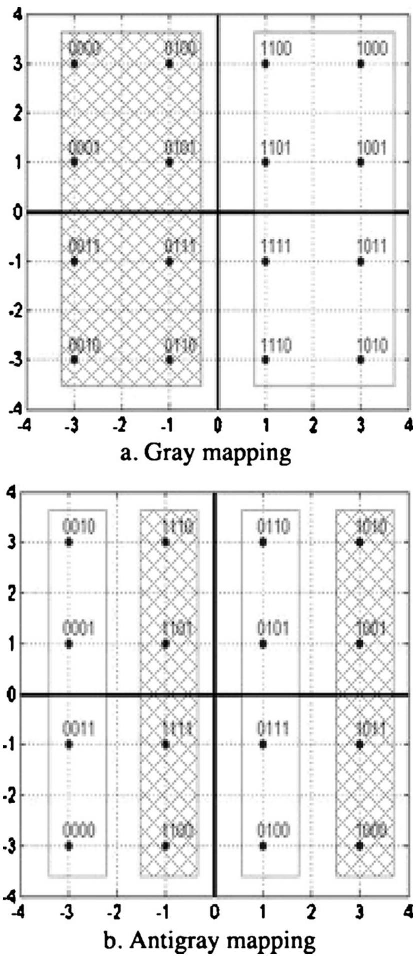

Fig. 2. Two typical 16QAM mapping.

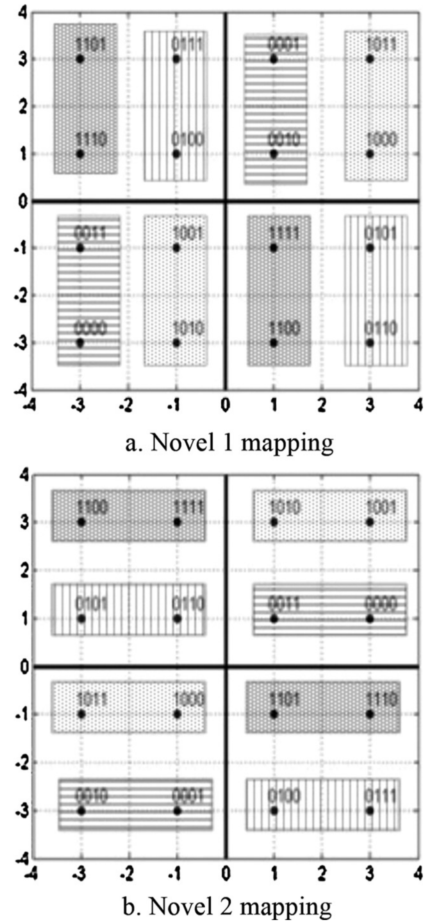

Fig. 3. Novel mapping proposed in the paper.

Here in this paper, the design criterion is focused on the mutual information whose target parameter is channel capacity.

4. Constellation mapping strategies

4.1. Classic constellation mapping schemes

The effects of different labeling methods are presented graphically in Fig. 2. Fig. 2a and b, respectively, illustrate the two typical mapping schemes of Gray mapping and Antigray mapping. It is recognized that four bits b_1, b_2, b_3, b_4 are mapped into one symbol in the 16QAM modulation scheme. It is obviously to see the principles of the bit allocation in Fig. 2a and b are different but with similarity. In concrete terms, while in the Gray mapping scheme the constellation points are divided into two regions according to the value of bit b_1 which may equal 1 or 0, in the meanwhile satisfying that constellation points in adjacent regions have only one different bit, the Antigray mapping follows the principle on the basis of above together with some transformations made to the square constellation.

Let α denotes the minimum squared Euclidean distance between constellation points, and presume having ideal feedback. Then based on the criterion of Euclidean distance spectrum, i.e., the formula for the harmonic mean of the minimum squared Euclidean distance, the influence of the Gray mapping scheme on the d_E^2 of each bits is described by

$$d_{E,b_1}^2 = \frac{8 \times 3\alpha + 8 \times \alpha}{16} = 2\alpha, \quad d_{E,b_2}^2 = \alpha, \quad d_{E,b_3}^2 = 2\alpha, \quad d_{E,b_4}^2 = \alpha$$

So the degree of bit protection belongs to b_1 and b_3 are higher than that of b_2 and b_4, which may affects the performance Gray mapping scheme attained at medium-to-high SNR region.

4.2. The proposed novel mapping scheme

A novel mapping scheme is proposed on the basis of design criterion aforementioned in the two typical schemes, which is revealed in Fig. 3. In consideration of the unequal degree of bit protection, a series of measures are taken to get an improvement in the novel mapping. Firstly, there exist different regions according to the value of $b_1b_2 \in \{11,01,00,10\}$, and $b_3b_4 \in \{01,10,11,00\}$, then the upper half of the mapping pattern is formed. Take the negated values of b_1b_2 in the upper half pattern as b_1b_2 at their symmetric position, and adopt similar means, the whole mapping scheme is accomplished as presented in Fig. 3a. Similarly, the influence of the novel mapping on the d_E^2 of each bits is described by

$$d_{E,b_1}^2 = \frac{\sqrt{13}\alpha + \sqrt{5}\alpha}{2}, \quad d_{E,b_2}^2 = \sqrt{5}\alpha, \quad d_{E,b_3}^2 = 2\sqrt{2}\alpha,$$

$$d_{E,b_4}^2 = \frac{\sqrt{13}\alpha + \sqrt{5}\alpha}{2}$$

Therefore, it is obvious to see the degree increase of the bit protection through a comparison between the novel mapping scheme and the Gray mapping scheme. Whereas the novel mapping scheme is not unique, so in accordance with the bit allocation method as

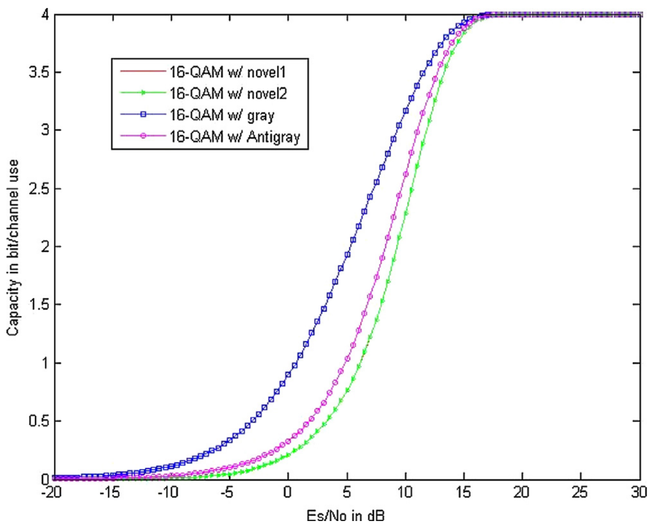

Fig. 4. The capacity of different signal mappings of BICM-ID system in AWGN.

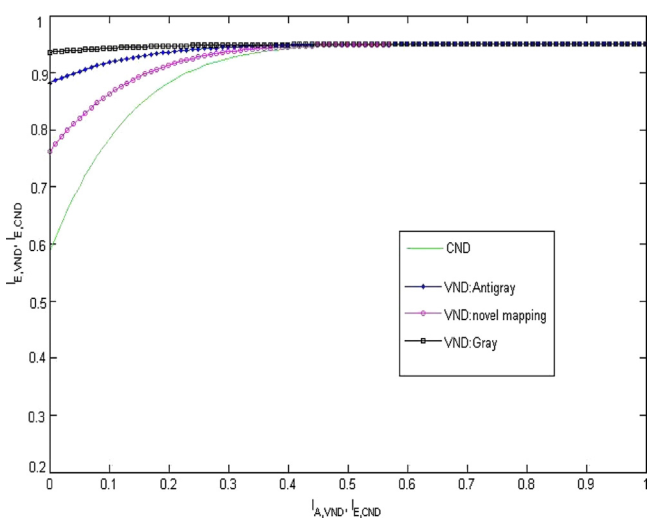

Fig. 5. EXIT chart for BICM-ID using various signal mappings (E_b/N_0 = 6.43 dB).

well as horizontally arranged, another novel mapping scheme can get as shown in Fig. 3b.

5. Performance simulation and analysis

5.1. Capacity result

To verify the superiority of the proposed novel mapping scheme, two experiments were taken. Moreover, in order to be consistent and comparable, the four mapping schemes in the same experiment are from the same structure together with a rate 2/3 capacity-approaching LDPC code, which has code-length of 64,800. The SNR is defined as the ratio E_s/N_0. Fig. 4 shows BICM-ID capacity result C against SNR for the different 16QAM constellations over an AWGN channel. It is seen that, the capacity curves belongs to novel mapping 1 and novel mapping 2 almost coincide, which provides the description that the two novel mapping schemes are equivalent due to their similar constructing methods while Gray mapping scheme keeps high capacity at the low-to-medium SNRs. As the SNR is increased, the novel mapping progressively outperforms the other two mapping schemes with higher growth rate. At medium-to-high SNR region, the excellent performance is obtained with the proposed novel mapping scheme. The capacity curves of the novel mapping scheme and the Gray mapping scheme have a crossover point at E_s/N_0 = 12.5 dB, and the former attains 1.58 bit/channel-use greater than the latter at higher SNRs.

5.2. EXIT curve analysis

Fig. 5 depicts the transfer functions in the EXIT chart for an AWGN channel of the mapping schemes investigated in this paper. As with the rate-2/3 codes, the code has a constant check-node degree of d_c = 10. Therefore, different EXIT curves of the VND depend on those various mapping schemes at a fixed code rate and channel SNR. Obviously, when the Gray mapping is applied the EXIT function of VND is almost flat, whereas the Antigray mapping has better EXIT performance. When it comes to the proposed novel mapping scheme, absolute advantage of decreased area within the EXIT chart's open tunnel is revealed from the simulated EXIT curve.

6. Conclusions

A novel mapping scheme, which is able to perform close to the capacity of the AWGN channel, is proposed for BICM-ID system in the optical transmission system in this paper. The superiority it brings has been verified through theoretical analysis and computer simulation. Compared to the traditional mapping schemes such as Gray mapping and Antigray mapping, the optimized BICM-ID system using the novel mapping scheme has the advantage of exceeding capacity of 1.58 bit/channel-use at high SNRs. In addition, another experiment concerning mutual information has been performed. The simulation result shows that the proposed novel mapping scheme and designed LDPC code can significantly match better with each other than other two mapping schemes by analyzing their EXIT curves.

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