Turbo-coded Ultra Long Haul System with Probabilistic Shaped 16QAM Modulation

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Abstract. With the rapid growth and development of 5G (5th Generation Mobile Communication Technology) and the incoming of 6G (6th Generation Mobile Communication Technology), the demand for high-speed and flexible communication solutions is becoming far more urgent. Within this paper, a novel code modulation scheme based on PS (probabilistic shaping) and Turbo code is proposed with its effectiveness is confirmed by the results of simulation. The results inform that in an optical fiber communication system with 56 Gb/s rate and 3000 km transmission distance, when the SNR (signal-noise ratio) is greater than 3.5 dB, the Turbo-coded PS-16QAM modulation format can achieve reliable transmission. The proposed scheme performs the best in BER (bit error ratio) and average launch power in the four cases of uniform 16QAM, PS-16QAM, Turbo-coded 16QAM with and itself. The proposed scheme is a potential solution in the future 5G communication.

Keywords. Turbo Code, Probabilistic Shaping, Ultra long haul system.

1. Introduction
Driven by "New Infrastructure" strategy, the 5G network has developed and would continue to develop steadily and rapidly in the next few years with strong momentum and led to the continuous expansion of the whole industrial scale. On June 6, 2021, IMT-2030 (6G) Promotion Group officially released the white paper "6G overall vision and potential key technologies" [1]. 6G communication will become a "nervous system" connecting the physical world and the intelligent world with TB (Terabyte) access rate, ms (microsecond) network delay, Mach motion speed and entirely intelligent interconnection. With the development of global data services, the demand for transmission capacity of communication system increases rapidly. Because of its wide transmission band, strong anti-interference ability, long transmission distance and good confidentiality, optical fiber communication has become one of the main communication modes in the world [2]. To cope with the growth of traffic, it is very important to develop high-speed and flexible optical fiber communication.

Turbo code has become the focus of information theory and coding theory since it was proposed. In the first paper on Turbo codes published in 1993, Berrou et al. [3] only gave the basic composition of Turbo codes and the principle of iterative decoding, without strict theoretical explanation and proof. Prof. J. Hagenauer et al. [4] clearly expounded the principle of iterative decoding for the first time, and systematically gave the soft output decoding algorithms of binary block codes and convolutional codes,
including MAP (maximum a posteriori) and Apriori-SOVA (soft output Viterbi algorithm) algorithms. They proposed an iterative stop decision condition based on relative entropy. Based on the computer simulation results, they pointed out that the performance of Turbo code composed of convolutional code is better at low bit rate, while the performance of Turbo code composed of block code is better at high bit rate. S. Benedetto et al. [5] [6] proposed the concept of uniform interleaver. Based on this, starting from the weight enumeration function of the code, using the joint bound technique, an upper bound of the average performance of Turbo codes on all interleavers is given. It is heuristically explained that with the increase of the number of iterations, the iterative decoding converges to the maximum likelihood decoding. This is the first time to systematically analyze the performance of Turbo codes.

As a new coding and modulation optimization technology, probabilistic shaping can expand channel capacity and improve the system flexibility. The actual optical communication system is always power limited, and there is always a certain gap between the system capacity and the theoretical value. To maximize the system capacity, shaping the constellation of the input signal and obtaining the shaping gain is a better solution [7] [8].

In 2015, Buchali et al. proposed to use PS-64QAM modulation format to realize 200-300 Gb/s adjustable network data rate, and the transmission distance of PS-64QAM is increased 40% farther than that of conventional 16QAM and 64QAM signals [9]. In 2016, the research group of Professor Georg Bicherer of Technische Universität München proposed a CCDM (constant component distribution matcher), which can change the uniformly distributed information sequence into a specific probability distribution information sequence [10]. In 2017, T. Yoshida proposed a post probabilistic shaping scheme suitable for optical communication PAM (pulse amplitude modulation) system, which can achieve a gain of 0.52 dB with an increase of 4% overhead [11]. In 2017, Idler of Bell Laboratories in Germany verified that 1Tb/s probabilistic shaping signal can be transmitted on 4 carrier super-channel. The spectral efficiency is about 5 (bit/s)/Hz, and the transmission distance in German backbone network is up to 1500 km [12]. In 2018, Qu et al. from the NEC laboratory in the United States proposed a general probabilistic-geometric hybrid shaping scheme based on two-dimensional probabilistic distribution matcher at the Optical Fiber Communications Conference and Exhibition, and proved through experiments that the performance of probabilistic-geometric hybrid shaping 32QAM is better than that of ordinary PS-32QAM and conventional 32QAM [13]. In 2019, Kaiquan Wu et al. of Hunan University performed PAS (probabilistic amplitude shaping) in the case of OFDM (orthogonal frequency division multiplexing) by combining with OCT (orthogonal circulant matrix transform) precoding [14]. In 2020, Junjie Ding et al. of Fudan University compared the GS (geometrically shaped) 32-QAM and PS 32-QAM in a bandwidth-limited IM-DD System [15].

In this paper, a scheme of Turbo-coded PS-16QAM is proposed. The scheme has significant advantages in BER and average launch power compared with the existing schemes. The results of simulation show that in an optical fiber communication system with 56 Gb/s rate and 3000 km transmission distance, when the SNR is greater than 3.5 dB, the Turbo-coded PS-16QAM modulation format can achieve reliable transmission.

2. Principles

In this paper, a scheme of Turbo-coded PS-16QAM is proposed. The PAS scheme based on the parity bit of system code needs to introduce an appropriate amount of additional information bits (Binary Data 2 in figure 1) according to the code rate to ensure that the number of symbols is consistent with the length of the symbol sequence output by CCDM. Therefore, the length ratio of Binary Data 1 and Binary Data 2 needs to be calculated additionally when transforming the code rate. The proposed scheme based on Turbo code can directly cascade CCDM and error correction code. They work independently and are more suitable for systems that need adaptive adjustment.
2.1. Encoding Process of Turbo Code

Figure 2 shows a block diagram of Turbo code, composed of two component encoders. The encoder is mainly composed of interleaver, component encoders, punctured matrix and multiplexer. In this encoder, the function of interleaver is to reset the bit sequence in the information sequence. The RSC (recursive system convolution) code is generally selected as component code, and the function of deletion matrix is to improve the coding code rate.

In the encoding process, the information sequence \( \{u_k\} \) with length \( N \) is sent to the Component Encoder 1 for encoding and directly sent to the multiplexer as system output \( \{x^1_k\} \). The interleaving Sequence \( \{u_n\} \) obtained from the interleaver \( I \) by getting passed with \( \{u_k\} \) is sent to the Component Encoder 2. Where \( n = I(k), 0 \leq n, k \leq N - 1 \). \( I(\cdot) \) is the interleaving mapping function, and \( N \) is the interleaving length, that is, the length of the information sequence. The verification sequences output by the two component encoders are \( \{x^1_k\} \) and \( \{x^2_k\} \) respectively. To improve the code rate and system spectral efficiency, the two check sequences can be deleted by the deletion matrix (obtain \( \{x^p_k\} \)) and then multiplexed with the system output \( \{x^s_k\} \) to form the codeword sequence \( \{c_k\} \).

2.2. Decoding Process of Turbo Code
Figure 3. Structure of Turbo decoding.

Figure 3 shows the basic structure of Turbo code decoder. Two SISO (soft input soft output) decoders in serial cascade make up the main structure of it. Both the encoder and the decoder use the same interleaver. The decoder 1 optimally decodes the component code RSC1, generates likelihood information about the information sequence $u$ per bit, and interleaves the "new information" to the decoder 2. The decoder 2 takes this information as a priori information, optimally decodes the component code RSC2, generates likelihood ratio information about the interleaved information sequence per bit, and then deinterleaves the information to decoder 1 for next decoding. It is stable that the external information of decoder 1 or decoder 2 tends to be after many iterations. And the asymptotic value of likelihood ratio is close to the maximum likelihood decoding of the whole code. As a result, deciding on the likelihood ratio obtains the best estimation $\hat{u}$ of information sequence $u$.

3. Simulation and Results
As shown in Figure 4, a probabilistic shaping 16QAM communication scheme based on Turbo coding error correction is proposed. Firstly, CCDM is used to transform the evenly distributed 0 and 1 bits into a symbol sequence obeying MB (Maxwell Boltzmann) distribution by introducing a certain redundancy. Then the symbols are demapped to obtain non-uniform 0- and 1-bit streams. Then, after Turbo coding, the PS-16QAM symbol sequence is remapped and input into the 3000 km optical fiber link for transmission. At the receiver, the LLR (log likelihood ratio) sequence is obtained by soft decision, and then Turbo decoding and BER are calculated. The system setup is shown in table 1 below.

![Figure 4. Structure diagram of a Turbo-coded PS-16QAM scheme.](image)

| Symbol rate (uniform) | Symbol rate (PS) | Single span distance (m) | Dispersion coefficient (s/m²) | Gamma (mW) | Attenuation (dB/m) | Span (km) |
|-----------------------|------------------|--------------------------|-------------------------------|------------|-------------------|----------|
| 10 GBaud              | 14 GBaud         | 1e5                      | 17e-6                         | 1.3e-6     | 0.2e-3             | 30       |

Table 1. System setup.
As shown in figure 5, having probabilistic shaping can evenly reduce the BER compared with uniform 16QAM. Having Turbo coding can make the BER drop sharply with the increase of SNR. Therefore, the advantages of Turbo coding and probabilistic shaping can effectively improve the BER performance of the system. As shown in Figure 6, the spectrum of PS-16QAM with symbol rate 14 GBaud is wider than that of uniform 16QAM with symbol rate 10 GBaud, indicating that the net rates of them are the same. Besides PS-16QAM has lower information entropy.

![Figure 5. BER/SNR of Uniform 16QAM, PS-16QAM, Turbo 16QAM and Turbo-coded PS-16QAM.](image)

![Figure 6. Spectrum diagram of uniform 16QAM and PS-16QAM.](image)

Figure 7 shows the constellations of uniform 16QAM (a) and PS-16QAM (b) with 3000 km transmission distance in optical channel. It is obvious that in the PS-16QAM constellation, the closer the signal points are to the center, the denser they are, and the farther away they are from the center, the sparser they are. Such a distribution can effectively reduce the bit error rate and average launch power.

![Figure 7. Constellation diagrams of uniform 16QAM and PS-16QAM through 3000 km optical channel.](image)

4. Conclusion
Probabilistic shaping is widely regarded as a promising technology because of its advantages of low bit error rate, low power consumption, high flexibility and low complexity. Turbo code has strong error correction ability to achieve better system performance. The proposed scheme skillfully combines convolutional code and random interleaver to realize the idea of random coding. At the same time, soft output iterative decoding is used to approximate maximum likelihood decoding.
In this paper, a scheme of Turbo-coded PS-16QAM is proposed. In the circumstance of 3000 km optical channel, Turbo-coded PS-16QAM scheme achieves lower bit error rate and average launch power. It provides a new way for the development of high-speed ultra long haul communication system.

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