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SPC-APPM coded modulation for deep-space optical communications*

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A coded modulation scheme for deep-space optical communications is proposed, which is composed of an outer single-parity-check (SPC)-based product code, an interleaver, a bit-accumulator and a pulse-position modulation (PPM). It is referred as SPC-APPM code, which is decoded with an iterative demodulator-decoder using standard turbo-decoding techniques. Investigations show that the scheme has the advantages of low encoding and decoding complexities, good performance and flexible code rate for all rates above 1/2. Meanwhile, simulation results demonstrate that the SPC-APPM provides the performance similar to the low-density parity-check-APPM (LDPC-APPM), superior to the LDPC-PPM and product accumulate code-PPM (PA-PPM), although inferior to serially concatenated PPM (SCPPM). At the bit error rate (BER) of 10^{-5}, the performance of SPC-APPM is about 0.7 dB better than LDPC-PPM and 1.2 dB better than PA-PPM.

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Error-correcting code (ECC) and pulse-position modulation (PPM) have been widely used in deep-space optical communications. Conventionally, the modulation and ECC operate independently as two different parts[1-5]. In Refs.[6] and [7], a coded modulation scheme called serially concatenated PPM (SCPPM) is proposed to combine the PPM and ECC as a whole. The accumulator and PPM modulation are considered as a single inner code, i.e., APPM code. Since the constraint length of the outer code of SCPPM is very short, the free distance can be smaller if excessive puncturing is done to increase the rate, which can result in the deterioration of bit error rate (BER) performance.

In Ref.[8], a scheme is proposed to replace the outer code with low-density parity-check (LDPC) code, which can be considered as LDPC-APPM. The investigation shows that the scheme can get high rates and also has excellent performance. However, the encoding complexity of its LDPC component is rather high. Besides, it is difficult to construct good LDPC codes with high rate for short block length[9].

Recently, single-parity-check (SPC)-based product codes have been investigated and show encouraging performance[5-9]. In this paper, we use SPC-based product code as outer code, and consider such a scheme as SPC-APPM. Simulation results show that the performance of SPC-APPM is as good as that of LDPC-APPM. Although the encoding structure of SPC-APPM is similar to that of product accumulate code-PPM (PA-PPM), the decoding structures are considerably different. Decoded with an iterative demodulator-decoder, SPC-APPM demonstrates much better performance than PA-PPM. In addition, the SPC-APPM code has all the advantages which the PA code possesses, such as low complexity, regular structure for all block size[9] and flexible rate adaptivity for all rates above 1/2.

The proposed encoder and transmitter of the system are shown in Fig.1(a). The endcoder consists of an outer code, an interleaver π_2, a rate-1 recursive accumulator and a PPM modulator. The accumulator and PPM modulation are considered as a single inner code. The outer code takes the form of two parallel branches of SPC codes concatenated via a random interleaver π_1.

As shown in the block diagram, a k-bit information sequence ($k = pt$) is split into p blocks, and t bits per block. Each block is parallelly encoded by two component SPC encoders to yield 2 check bits, 1 bit for each component SPC encoder. Hence, the outer code length is $n=p(t+2)$, and the rate is $R=t/(t+2)$. The output of outer code passes through a random interleaver π_2, followed by a rate-1 recursive accumulator, and then is modulated before finally being put

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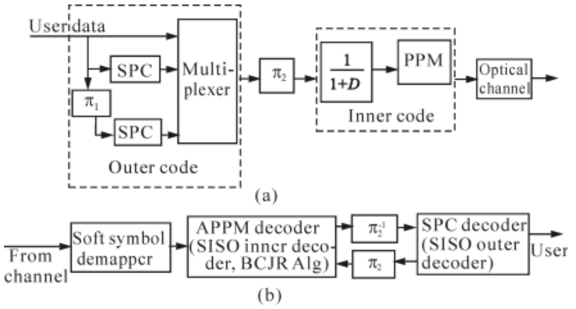

Fig.1 System models of (a) SPC-APPM encoder and (b) SPC-APPM decoder

onto the channel.

The channel output is modeled as Poisson process, with mean of n_b in a noise slot and $n_b + n_s$ in a signal slot[6]:

$$p(k\,|\,1) = \frac{(n_s + n_b)^k \exp[-(n_b + n_s)]}{k!}, \tag{1}$$

$$p(k\,|\,0) = \frac{n_b{}^k \exp[-n_b]}{k!} \quad . \tag{2}$$

The receiver consists of a demapper and a decoder. The demapper computes the channel symbol log-likehoods, and delivers them to the inner soft-in soft-out (SISO) decoder.

The decoder, correspondingly, consists of four blocks, which are the inner decoder, the bit de-interleaver π_2^{-1}, the outer decoder and the bit interleaver π_2. A block diagram of the iterative demodulator-decoder is shown in Fig.1(b). The inner decoder operates with the SISO algorithm proposed in Ref.[6]. The outer decoder operates with the message-passing (MP) algorithm[9].

Let $c^{(j)}$ denote the PPM symbol with a pulse in the jth slot at the transmitter, and let $y = (y_0, y_1, \cdots, y_j, \cdots, y_{M-1})$ denote the soft outputs of a PPM symbol from the channel, so the log-likehood of $c^{(j)}$ given with y can be derived from the channel transition density[6],

$$\pi(c^{(j)}; I) = \log p(y\,|\,c^{(j)}) = y_j \log(1 + \frac{n_s}{n_b}) + \text{constant}, \tag{3}$$

where $\pi(c^{(j)}; I)$ is the soft symbol log-likehood from the demapper. As can be counteracted during the decoding computation, the constant is usually ignored when initializing the decoder.

In the SPC-APPM scheme, the decoder works with an iterative demodulating-decoding algorithm. There are two iterations in the decoding of SPC-APPM. One is outer iteration (outer loop) between the inner code and outer code, and the other is local iteration (local loop) between two component SPC codes in outer code. The outer iteration begins with the inner code. With the symbol log-likehoods from the demapper and the extrinsic information (EI) from the outer decoder, the inner decoder computes a posteriori probability bit log-likehoods ratio (LLR), and sends them back to the outer decoder as EI. On initialization, the EI from outer decoder is set zero. The inner decoder operates with forward-backward algorithm, which is presented in Ref.[6]. It should be noted that the inner decoder is a symbol and decoder, and the inputs from demapper are symbol log-likehoods computed by Eq.(3), rather than bit LLR.

EI from the inner decoder is sent to the de-interleaver, and then to the outer decoder. The decoding process of the outer decoders is a local iteration, in which EI is passed between the upper branch and the lower branch to update the inputs. The local iteration starts from the upper branch. With EI from the inner code and the lower branch, the upper branch computes LLR, and passes it to the lower branch as EI. In return, the lower branch uses EI from the inner code and the upper branch to compute LLR and passes it back to the upper branch. When the local iteration ends, LLR from the lower branch is exported and sent to the inner decoder. The outer SPC decoder is a bit and a posteriori probability decoder, which decodes with MP algorithm proposed in Ref.[9]. When the outer iteration is finished, LLR from the outer code is exported to make a hard decision.

Since SCPPM, LDPC-APPM and SPC-APPM have the uniform inner code, the complexity is determined by the outer code. As SPC-APPM and LDPC-APPM have the similar decoding structure (local iteration and outer iteration), with the results in Refs.[8] and [9], it is easy to come to a conclusion that the SPC-APPM has lower complexity than LDPC-APPM.

As SCPPM is a kind of serially concatenated convolutional code (SCCC) which is decoded with Bathl-Cocke-Jelinek-Raviv (BCJR) algorithm, its outer decoder complexity can be evaluated as in Ref.[14]. According to the results in Refs.[8], [9] and [14], it can be inferred that the SPC-APPM has lower complexity than SCPPM.

In all simulations, randomly generated interleavers are employed, and the channel is the Poisson channel given by Eqs.(1) and (2) with n_b=0.2, M=64 and slot duration of T_s =32 ns. For the convenience of comparison, the inner codes of SCPPM and LDPC-APPM are the same as Ref.[6]. The PA-PPM code is not decoded with iterative demodulating-decoding algorithm, but with belief propagation (BP) algorithm proposed in Ref.[9] after PPM demodulation. For the convenience of comparison, in the following figures, x-axis is signal to noise ratio of SNR=10lg $(n_s/(MT_s))$, which is the same as Refs.[6-8].

Fig.2 shows the BER performance of the SPC-APPM, SCPPM, LDPC-APPM, LDPC-PPM and PA-PPM at rate of 1/2 with code lengths of 4608 and 2304. The size of interleaver equals the code length, and the LDPC-PPM is non-interleaved. The iterations of SCPPM and LDPC-PPM are 15 and 25, respectively. As for the SPC-APPM, LDPC-APPM and PA-PPM, the local and outer iterations are both 15. As can be seen, the larger the SPC-APPM code length, the steeper the performance curve. It can be immediately seen from Fig.2 that the SPC-APPM code provides the performance similar to LDPC-APPM, better than LDPC-PPM, although it suffers a loss of a few tenths of a decibel compared with SCPPM. The SPC-APPM code shows a significant performance improvement with respect to the PA-PPM. It demonstrates that the iterative demodulator-decoder approach has better performance than the non-iterative approach.

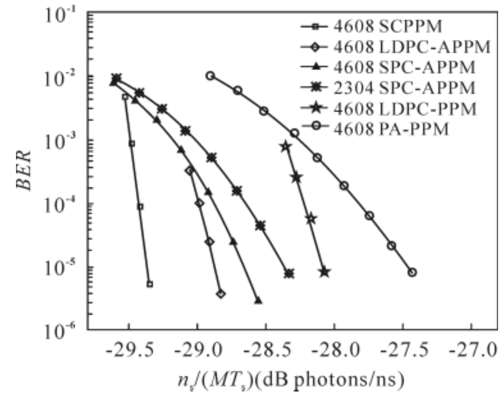

Fig.2 BER performance at rate of 1/2 with code lengths of 4608 and 2304

Fig.3 plots the BER performance of the SPC-APPM at high rates with the code length of 4608 and the iteration of 15. The simulated codes have rates of 0.67, 0.75, 0.83 and 0.91, corresponding to t = 4, 6, 10 and 20, respectively. Since its rate is $R = t/(t + 2)$, it is flexible to get high rates. As for the SCPPM codes, high rates can be achieved by puncturing the outputs of the outer convolutional code. However, for SCPPM codes with very high rate, the required amount of puncturing is rather large. The LDPC-APPM code can obtain high rate, but the rate is not flexible, because the rate of LDPC code is determined by the sparse matrix. When the rate changes, the sparse matrix should be changed correspondingly. For SPC-APPM, it only needs to modify the parameters when rate changes.

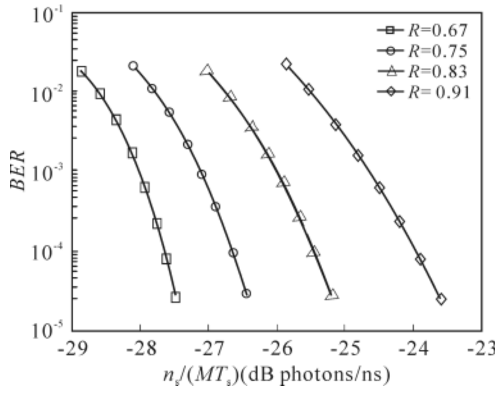

Fig.3 BER performance of SPC-APPM for different rates with the code length of 4608

Fig.4 shows the performance of the SPC-APPM with various iterations at the rate of 1/2, the length of 4608, the local iterations of m=5, 10, 15, and the outer iterations of n=3, 6, 9. It is shown that the performance improves as the iteration increases. Compared with local iteration, outer iteration has more influence upon the performance, because there are m local iterations in one outer iteration. From Fig.4 we can see that the improvement mitigates as the iteration increases. Simulation results show that when m >10 and n > 9, the performance does not improve rapidly any longer as m and n increase.

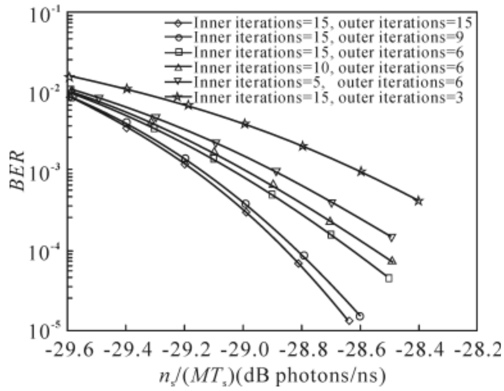

Fig.4 BER performance of SPC-APPM with different iterations at rate of 1/2 and code length of 4608

All the simulations are only performed down to 10^{-5}. However, the extrinsic information transfer (EXIT) chart provides a powerful means to analyze the BER floor[15]. By examining the extrinsic information passed between the inner and outer decoders, we find that the iterative decoding converges. It indicates that the BER decreases to a very low value as the iteration increases.

The SPC-APPM coded modulation scheme has the advantages of flexible rate and low decoding complexity. By simulation and EXIT analysis, we find that it has good performance. It provides BER performance similar to LDPC-APPM, better than LDPC-PPM and PA-PPM. We also investigate the influence of the iteration on BER performance. Results show that the BER performance improves as the iteration increases. For the limitations of space, the effects of interleaver's type, interleaver's size and the order of modulation on BER performance are not discussed here.

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