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Low complexity Reed–Solomon-based low-density parity-check design for software defined optical transmission system based on adaptive puncturing decoding algorithm

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ABSTRACT

We propose and demonstrate a low complexity Reed–Solomon-based low-density parity-check (RS-LDPC) code with adaptive puncturing decoding algorithm for elastic optical transmission system. Partial received codes and the relevant column in parity-check matrix can be punctured to reduce the calculation complexity by adaptive parity-check matrix during decoding process. The results show that the complexity of the proposed decoding algorithm is reduced by 30% compared with the regular RS-LDPC system. The optimized code rate of the RS-LDPC code can be obtained after five times iteration.

1. Introduction

The exponential Internet traffic growth has placed huge transmission capacity demand on the underlying infrastructure of optical transmission system [1]. As the increase of capacity, the on-demand bandwidth provisioning capability is emerging as crucial for the system. In order to cope with the high-capacity and flexibility requirements, the software defined optical transmission system for more efficient and flexible traffic planning has attracted much attention [2–4]. In software defined optical transmission system, high optical capacity can be achieved by increasing the spectral efficiency, which can reach capacity of 100 Gb/s, 400 Gb/s and even 1 Tb/s beyond [5–7]. Generally, the spectral efficiency can be improved by increasing the number of signal levels, such as quadrature phase shift keying (QPSK), 32 quadrature amplitude modulation (QAM) and 128QAM [8–10]. In order to provide flexible allocation for the optical signals, it requires the switch node to enable dynamic scheduling or routing for different signals, which is generally realized by the flexible-grid filters or wavelength selective switches [11]. However, the dynamic scheduling would lead to different penalties for signals due to the filter impairment or data rate variety, which results in quite different optical signal-to-noise ratios (OSNRs) at destination sides. Besides, signal with high spectral efficiency always requires more rigorous OSNR during transmission. In order to improve the signal performance under fluctuated OSNR, it is essential to design and implement soft decision forward error correction (SD-FEC) in this system, which could change the error correction strength according to channel conditions.

Recently, many approaches for powerful SD-FEC have been intensively developed. Combined Turbo code and low-density parity-check (LDPC) code has been proposed in Refs. [12,13], which has superimposed coding gain in practical use. Several LDPC block codes (LDPC-BC) schemes with 10+dB net coding gain are reported in Refs. [14,15], while LDPC convolution codes (LDPC-CCs), as the counterpart of LDPC-BCs, have been investigated in Ref. [16]. For conventional scheme, several LDPC codes can be used for different rates, but the implementation complexity will be increased remarkably [17]. Furthermore, the previous work has not considered the fluctuation of OSNR induced by the dynamic switching in the elastic software defined optical transmission system.

In this paper, we propose a novel RS-LDPC scheme for software defined optical transmission system based on adaptive puncturing decoding algorithm. It can provide dynamic puncturing at the receiver according to the channel OSNR condition, which offers improved bit error ratio (BER) performance with low complexity. A software defined optical transmission system with adaptive RS-

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LDPC code is simulated to demonstrate the feasibility of the propose method.

2. Theory and algorithm

Fig. 1 illustrates the flow diagram of the proposed adaptive puncturing decoding algorithm. Assuming the total length of the signal frame is l_{total} and the maximum length of the puncturing is Δ_{max}, the slicing step can be expressed as

$$\Delta_i = \Delta_{max} * \lambda^{(l_{i-1} - l_{total})} \tag{1}$$

where λ is a parameter related to puncturing speed. Δ_i is the puncturing length based on the previous decoding length of l_{i-1}, and the ith decoding length can be represented by

$$l_i = l_{i-1} - \Delta_i \tag{2}$$

From Eq. (1), it can be seen that Δ_i will exponentially increase or decrease with l_{i-1}. The exponential puncturing function would lead to a faster response of slicing, which reduces the computation complexity as well as failure probability of LDPC with short length.

At the start of the decoding, we choose an empirical value of $R_{default}$ as the initial code rate and the default decoding length can be expressed as

$$l_{default} = l_{total} \frac{R_0}{R_{default}} \tag{3}$$

where R_0 is the code rate. Thus the initial puncturing code length can be represented by

$$\Delta l_{default} = l_{total} \times (1 - \frac{R_0}{R_{default}}) \tag{4}$$

During decoding, the puncturing is executed by removing a set of variable nodes from its check matrix. In our scheme, the variable nodes of the bipartite graph are grouped in accordance with the degrees, where variable nodes with lowest degree distribution would be punctured firstly. It means that code words with least information would be erased, which is shown in Fig. 2. The codes are punctured according to priority of columns weight in the check matrix. The puncturing process begins by puncturing $\Delta l_{default}$ parity bits before calculating the BER. Log-likelihood ratio belief propagation is adopted for LDPC decoding. During decoding iteration, the unpunctured variable nodes receive initial information from the channel and send to their neighbor check nodes. After check nodes and variable nodes updating, all the information of variable nodes will be sent for final decision. After BER calculation, the algorithm will judge whether the channel condition is fine. If the received OSNR is better than the threshold, it means that the channel condition is fine and the puncturing length can be increased to fasten the decoding of the signal. If the received OSNR is worse than the threshold, it means the channel condition has deteriorated and the puncturing length would be reduced to avoid decoding failure until the BER is beyond the threshold. For linear puncturing function, the number of recovered codes is limited during iteration, which might result in decoding failure. Compared with linear puncturing, more codes can be recovered to achieve better BER performance due to the exponential feature of slicing step. The reducing is performed by reversed slide, which can be presented by

$$l_i = l_{i-1} + \alpha \Delta_i \tag{5}$$

Here α is a tunable weight factor, which can improve the speed of decoding decision. The value of α is decided according to the channel condition. It can be set as a small value when the channel is under slight fluctuation. In this case, the decoding length for each frame can be maintained in small range to improve the code rate. Otherwise, α can be set as a larger value to help adapt the fast variety of channel condition.

The flow of puncturing decoding algorithm is summarized as follows.

1) Initialize parameters to the default code length.

   $\Delta_i = \Delta l_{default}$, $l_i = l_{default} (i = 1)$

2) Calculate the BER.
3) Check if BER performance is above threshold

   if SNR $> =$ threshold.

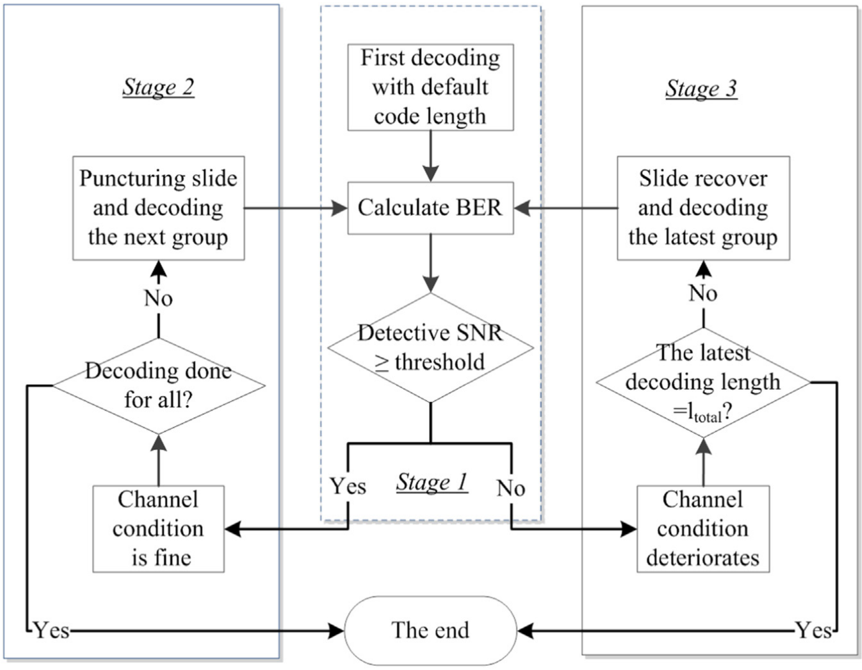

Fig. 1. The flow diagram of proposed adaptive puncturing decoding algorithm.

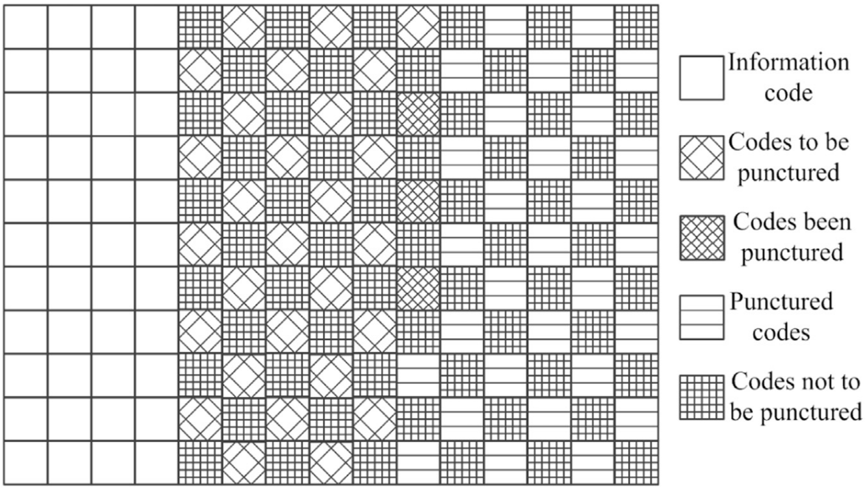

Fig. 2. Puncturing process of received codes.

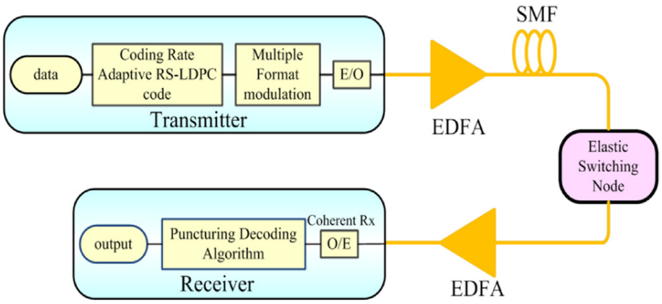

Fig. 3. The simulation setup of the proposed scheme (E/O: electrical to optical; EDFA: Er-doped fiber amplifier; SMF: single mode fiber; O/E: optical to electrical).

$$l_i = l_{i-1} - \Delta_i,\ i = i + 1\ \ (i > 1)$$

else

$$l_i = l_{i-1} + \alpha\Delta_i,\ i = i + 1\ \ (i > 1)$$

4) Go to step 2.

3. Results and discussion

The simulated setup of adaptive RS-LDPC coded software defined optical transmission system is illustrated in Fig. 3. At the transmitter, a combined RS code and LDPC code is adopted for the coding modulation with adaptive coding rate. A (255, 223) RS code over GF(8) is concatenated with the irregular LDPC code, where the original code of LDPC is set to be (1020, 510). During encoding, every encoded 255 octal codes are seen as one frame. The transmission link is consisting of 200 km single mode fiber (SMF), Er-doped fiber amplifier (EDFA) with 5 dB noise figure and elastic switching node. In the simulation system, the channel noise is mainly caused by the amplified spontaneous emission (ASE) of EDFA and filtering loss at the switching node. At the receiver side, a coherent receiver is used to detect the optical signal. The puncturing decoding algorithm is used to demodulate the detected signal. During demodulation, the default decoding length is set to be 1020, λ=1.0094 and the weight factor α is set to be 2.

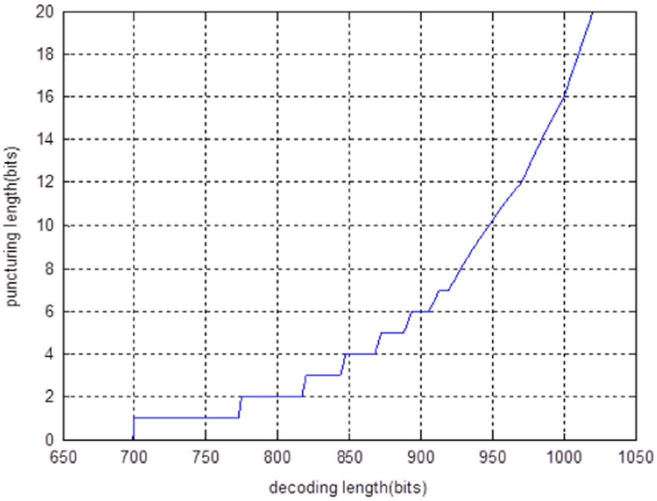

Fig. 4. The relationship between puncturing length and decoding length.

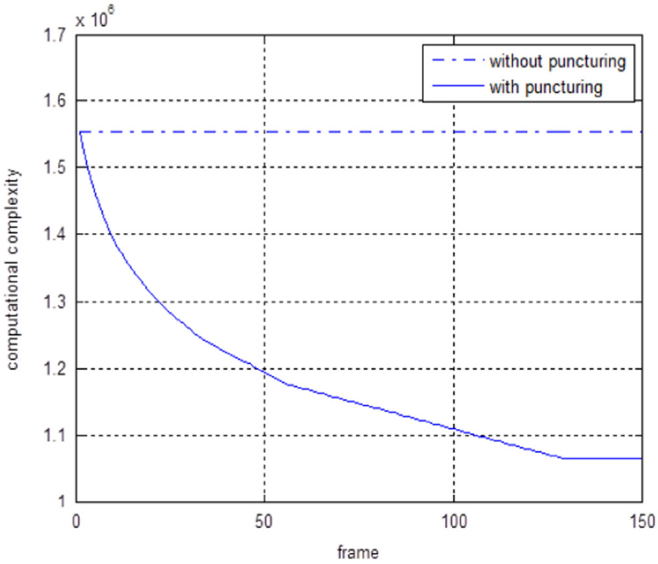

Fig. 5. Complexity between regular decoding and puncturing decoding.

Fig. 4 shows the relationship between the puncturing length and decoding length. During simulation, we have Δ_{max}=20, l_{total} =1020 bit and $l_{default}$=700 bit. It can be seen that the puncturing length increases fast as the raise of decoding length, which indicates a fast response of puncturing slide. Next, we investigate the computational complexity with and without puncturing. In our scheme, Log-likelihood ratio belief propagation is adopted for the decoding and the computational complexity is defined as the operation times at the receiver, including multiplication, addition

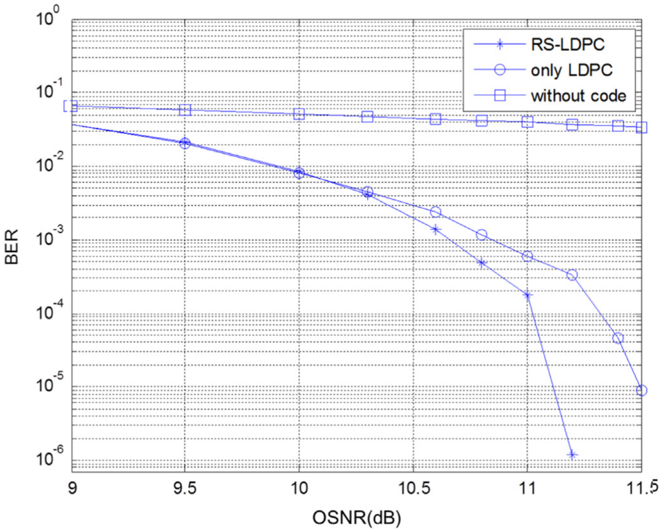

Fig. 6. Measured BER curves for different channel codes.

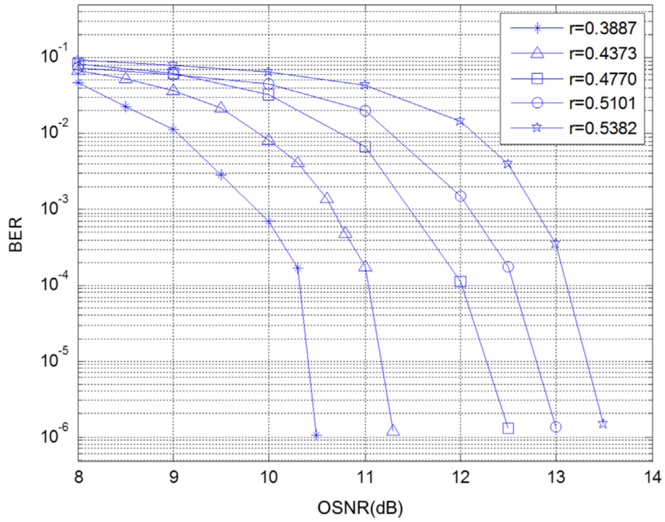

Fig. 8. The BER performance for different puncturing ratios.

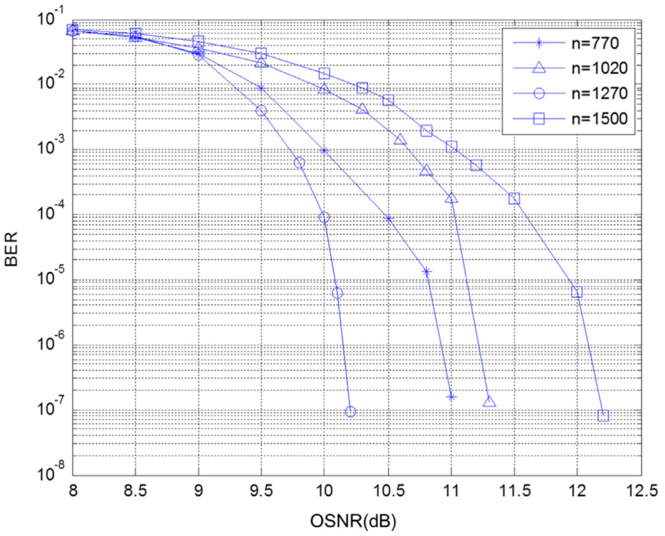

Fig. 7. The BER performance for different code lengths.

and division operations [18,19]. The measured result is illustrated in Fig. 5, where we adopt same decoding length of $l_{total}=1020$ bit. For the decoding with puncturing, it can be seen that the average computational complexity gradually reduces as the increase of frame number. When the frame number is beyond 130, the complexity achieves to a minimum constant value. The complexity without puncturing keeps a larger constant value of 1.55×10^6. The computational efficiency is improved by 30% after puncturing. In practice, the initial decoding length is usually set to be default code length of $l_{default}$ instead of l_{total}, which varies with channel condition. Better decoding efficiency can be further achieved by properly setting the values of Δ_{max} and λ. For example, we can choose shorter default code length for higher OSNR case and longer default code length for lower OSNR case. On the other hand, the time complexity of decoding can be reduced by proper hardware design. The hardware of LDPC decoder mainly consists of variable node processing units (VNU), check node processing units (CNU) and parity calculating units (PCU). For VNU and CNU, they are in serial working mode. However, PCU is independent of CNU and operates after the VNU. Therefore, PCU and CNU can be designed to work in parallel mode to reduce the time complexity of decoding.

Then we compare the BER performance under different channel codes and the BER curves are shown in Fig. 6, where we have measured the signal with RS-LDPC code, with only LDPC code and without code. Obviously, the BER performance is improved with channel code. When the OSNR is less than 10.3 dB, signals with only LDPC code and with RS-LDPC code have similar BER performance. As the increase of OSNR, signal with RS-LDPC code outperforms that with only LDPC code because the RS code can improve the error floor of LDPC code. The waterfall area appears at about 11 dB for the signal with RS-LDPC code. In order to reduce the redundancy and time delay, the RS code is set as outer code and LDPC code is inner code. Because RS code has got lower redundancy, it would not increase the redundancy of LDPC. Besides, the residual error of LDPC can be removed by RS code, which improves the error floor of LDPC code.

Fig. 7 illustrates the BER performance with different coding lengths, where 770 bit, 1020 bit, 1270 bit and 1500 bit are measured. It can be seen that the BER performance is not always proportional to the code length. When the code length is 1270 bit, the BER performance is better than the others. It is mainly because the low-weight codes would occur with double-diagonal submatrix in the parity check matrix. This situation can be eliminated by short cycle check with algebraic method. The proper design of the parity check matrix can increase the randomness and remove the row correlation, which solves the problems of short cycle and low-weight in LDPC code.

Fig. 8 shows the BER performance with different puncturing ratios. It can be observed that the BER curves for different ratios are close to each other when the OSNR is below 10 dB. In low OSNR region, less puncturing can help to improve BER performance. If the OSNR threshold is defined (e.g. 13 dB), we can choose a proper puncturing ratio according to the quality of service (QoS) of signal in the software defined optical system.

4. Conclusion

In this paper, a novel RS-LDPC scheme based on adaptive puncturing decoding algorithm is proposed for software defined optical transmission system. The puncturing can be adjustable by changing column weight of check matrix. The complexity and BER performance are analyzed in the simulation. Compared with conventional signal, the computational complexity can be reduced by 30% with improved BER performance. The results indicate the proposed algorithm a potential solution for future FEC in next generation software defined optical transmission system.

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