Improved forward error correction technology of RS-LDPC cascade code in optical transport network*

MA Xiurong**, **MA Xiaohang, and SHAN Yunlong**

Engineering Research Center of Optoelectronic Devices and Communication Technology, Ministry of Education, Tianjin University of Technology, Tianjin 300384, China

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With the continuous development of optical communication and the increase in data transmission volume, optical transport network (OTN) has become the focus of research in next-generation transmission networks. In the process of data transmission, errors caused by noise often occur, resulting in an increase in the bit error rate (*BER*) and a decrease in the performance of the optical communication system. Therefore, we use forward error correction (FEC) technology in OTN for error control to improve the transmission efficiency of signals in OTN and reduce the *BER*. Standard FEC technology uses RS(255,239) code. On this basis, since the performance of low density parity check (LDPC) code is close to the Shannon limit, we propose a method of cascading RS code and LDPC code. Applying this improved FEC technology to OTN, the simulation results show that the improved FEC technology has a reduced *BER* compared with the standard FEC technology. When the *BER* is at the 10^{-3} level, the performance is improved by about 1.7 dB.

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In recent years, the development of optical communication technology has gained rapid momentum. Optical communication network has higher requirements for transmission distance, transmission capacity and transmission rate. Optical transport network (OTN) is a next-generation transmission network regulated by the International Telecommunication Union (ITU-T). It combines the advantages of synchronous digital hierarchy (SDH) and wavelength division multiplexing (WDM) technology to support a variety of service signal mapping, which has attracted great attention from researchers[1-4]. However, in high-speed and long-distance optical transmission systems, due to the attenuation, dispersion and nonlinear effects of optical signals in optical fibers, errors will inevitably occur[5,6]. According to the G.709 launched by ITU-T and other suggestions, we study forward error correction (FEC) technology and optimize it to enhance the transmission performance of OTN[7-10].

The first-generation FEC technology is mainly represented by a single encoding of RS(255,239). The second-generation FEC technology uses cascaded codes and iterative decoding methods. The third-generation FEC technology focuses on higher-performance patterns, such as low density parity check (LDPC) codes, Turbo codes, etc[11,12]. According to the error control coding theory, in order to improve the error correction ability, long codes should be selected as much as possible, but as the code length increases, the bit rate will decrease, the amount of decoding calculations will also increase, and the equipment complexity is higher. Using the method of cascading codes, a long code with excellent performance but not easy to achieve can be graded in the form of multiple short codes. Compared with a single coding method, the error correction performance of the system can be greatly improved[13,14].

Because the RS code is simple to encode and decode and has strong error correction capabilities, the standard FEC technology in the OTN uses RS code. On this basis, as a representative of the third-generation FEC technology, LDPC code uses an iterative decoding algorithm and its performance is close to the Shannon limit, so we will focus our research on LDPC code. In Ref.[15], a scheme for cascading RS codes with LDPC codes is proposed. And compared the performance of different code lengths and iteration times, Ref.[16] proposed to use RS code as the outer code to construct RS-LDPC cascade code to eliminate the false leveling phenomenon of LDPC, and an iterative process is added between the outer code and the inner code, which can effectively improve the overall performance of the cascade code. The simulation results show that the proposed cascade code has good performance and small rate loss.

In order to improve the transmission performance of OTN, this paper adopts the method of cascading RS code

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** E-mail: maxiaohang9789@163.com

and LDPC code to implement FEC technology, where the outer code is RS code and the inner code is LDPC code. In addition, the performance of cascaded codes using different LDPC codes is studied from the three aspects of code length, code rate and iteration times, and finally a suitable pattern scheme is selected for application in OTN. The simulation results show that the bit error rate (BER) of this method is low and the error correction ability is significantly improved compared with when it is not encoded.

Fig.1 shows the standard frame format in OTN. It is a frame format of 4 rows and 4 080 columns. The first 16 rows of each row are listed as overhead bytes. User information is stored in columns 17 to 3 824, and columns 3 825 to 4 080 are used for FEC, where each row is carried out independently. The standard FEC technology in OTN includes two processes, data interleaving and RS(255,239) encoding and decoding. The working principle is to first use byte interleaving to divide 1 line of the optical transform unit (OTU) frame into 16 sub-lines, and use RS(255,239) code for each sub-line for FEC.

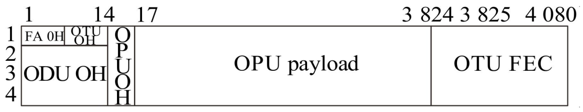

Fig.1 OTN standard frame format

Interleaving is to disrupt and rearrange the original data sequence according to certain rules, so that the randomness of the adjacent symbols of the interleaved sequence is enhanced. Its effect is that when a sudden error occurs in the data sequence, it can be discretized by interleaving and become a random error, which can be corrected by FEC technology. When performing FEC technology in OTN, byte interleaving is used to divide 1 row of the OTU frame into 16 sub-rows, as shown in Fig.2.

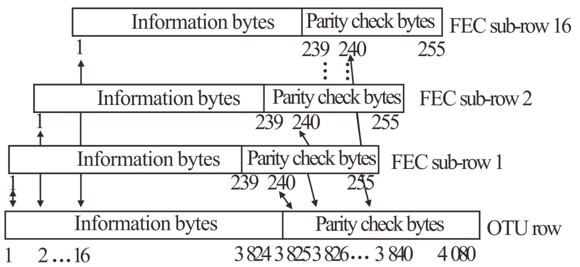

Fig.2 FEC data interleaving

The specific method is to interleave the first 3 824 information bytes of each row of the OTU frame by bytes, and interleave them into 16 sub-rows. The first 16 bytes of each row become the first byte of 16 sub-rows, the second group of 16 bytes of each row, that is, the first 17 to 32 bytes become the second byte of 16 sub-rows, and so on. The byte interleaving method is after that. The 16 sub-lines obtained after interleaving are completed, each line has 239 information bytes. RS(255,239) code is used for FEC for each sub-line, and 16 check bytes are added to each sub-line after the encoding is completed, for a total of 255 bytes.

The RS(255,239) code is calculated in the Galois domain $GF(2^8)$, and its generating polynomial is

$$g(x)=\prod_{i=1}^{16}\left(x-\alpha^{i}\right), \tag{1}$$

where α^i is the root of the original polynomial $x^8+x^4+x^3+x^2+1$.

Therefore, the generating polynomial of the RS(255,239) code expands to

$$\begin{aligned} g(x)=\prod_{i=1}^{16}(x-\alpha^{i})=(x-\alpha)(x-\alpha^{2})(x-\alpha^{3})\cdots(x-\alpha^{16})= \\ x^{16}+59x^{15}+13x^{14}+104x^{13}+189x^{12}+68x^{11}+209x^{10}+ \\ 30x^{9}+8x^{8}+163x^{7}+65x^{6}+41x^{5}+ \\ 229x^{4}+98x^{3}+50x^{2}+36x+59. \end{aligned} \tag{2}$$

Information sequence is (m_0, m_1,…, m_{238}), and the information polynomial is

$$m(x)=m_0+m_1x+m_2x^2+\cdots+m_{238}x^{238}. \tag{3}$$

Divide the information code polynomial by the generated polynomial to obtain the remainder formula as

$$r(x)=x^{15}m(x)\bmod\left[g(x)\right], \tag{4}$$

where $r(x)$ is the check polynomial, and the check sequence obtained is (r_0, r_1,…, r_{15}).

So, the codeword polynomial of RS(255,239) is

$$c(x)=x^{15}m(x)+r(x). \tag{5}$$

The system code of RS(255,239) is (m_0, m_1,…, m_{238}, r_0, r_1,…, r_{15}).

For a sub-line of FEC, the RS(255,239) encoding process is shown in Fig.3.

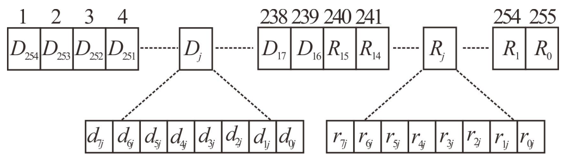

Fig.3 RS(255,239) encoding process in OTN

The FEC codeword consists of information bytes and check bytes, and its polynomial is expressed as

$$C(x)=I(x)+P(x). \tag{6}$$

The information byte polynomial $I(x)$ is expressed as

$$I(x)=D_{254}x^{254}+D_{253}x^{253}+\cdots+D_{16}x^{16}, \tag{7}$$

where D_j (j=16, 17,…, 254) is the information byte. In the FEC sub-line, D_{254} represents the first byte and D_{16} represents the 239th byte. Each information byte D_j consists of 8 bits, which can be expressed as

$$D_j=d_{7j}\cdot\alpha^{7}+d_{6j}\cdot\alpha^{6}+\cdots+d_{j}\cdot\alpha+d_{0j}, \tag{8}$$

where d_{7j} is the most significant bit of information byte D_j, and d_{0j} is the least significant bit of information byte D_j.

The check byte polynomial $P(x)$ is expressed as

$$P(x)=R_{15}x^{15}+R_{14}x^{14}+\cdots+R_1x+R_0, \tag{9}$$

where R_j (j=0, 1,…, 15) is the check byte. In the FEC sub-line, R_{15} represents the 240th byte and R_0 represents the 255th byte. Each check byte R_j consists of 8 bits, which can be expressed as

$$R_j = r_{7j}\cdot\alpha^7 + r_{6j}\cdot\alpha^6 + \cdots + r_j\cdot\alpha + r_{0j}, \quad (10)$$

where r_{7j} is the most significant bit of check byte R_j, and r_{0j} is the least significant bit of check byte R_j.

The calculation formula of the check byte polynomial is

$$R(x) = M(x)\bmod\left[g(x)\right]. \quad (11)$$

RS(255,239) decoding can be divided into five steps, and the flow chart is shown in Fig.4.

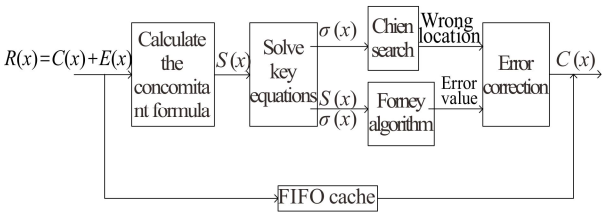

Fig.4 RS(255,239) decoding flow chart

The first step is to calculate the concomitant formula S based on the receiving polynomial. In the second step, the BM iterative algorithm is used to solve the error position polynomial. In the third step, the Chien search method is used to obtain the root of the concomitant formula S, and the number of wrong positions is the reciprocal of the root. The fourth step is to use the formula to calculate the error value. The fifth step is to receive the polynomial minus the error polynomial to complete the error correction.

Next, we will conduct a simulation analysis of the performance of standard FEC technology.

Fig.5 shows the use of standard FEC technology in OTN, that is, the use of RS(255,239) coding algorithm, compared with the error correction performance of unused FEC technology.

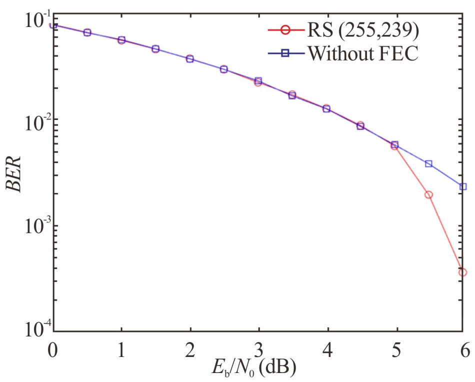

Fig.5 Standard FEC simulation results

As can be seen from the simulation result diagram, after the signal-to-noise ratio is greater than 5 dB, the performance of the standard FEC technology begins to be significantly better than that of the unused FEC technology, and the BER is greatly reduced, and as the signal-to-noise ratio increases, the more the BER improves. This is because when RS(255,239) code is used for FEC, the information bytes can be supervised due to the introduction of check bytes. When an error occurs during transmission, the error can be detected and corrected in a timely manner. From the vertical view in the figure, it can be seen that when the BER is 10^{-3}, the BER performance of the standard FEC is approximately 0.5 dB higher than that of the unused FEC technology.

In order to improve the reliability of the transmission process, we can grade a long code with excellent performance but not easy to achieve in the form of multiple short codes to form a cascade code. Compared with a single coding method, the error correction performance of the system can be greatly improved. In addition, in order to better solve the sudden errors that occur during transmission, we can add an interleaving process after the external code is encoded, and the encoded data is disrupted and rearranged to improve its randomness, and then code the inner code.

In the above analysis, we know that the encoding and decoding of RS code is simple and RS code has strong error correction capabilities, it is widely used in FEC technology. And the performance of LDPC code is very good. So we propose a scheme that uses RS code as the outer code in the cascaded code and LDPC code as the inner code in the cascaded code. The block diagram of the cascade design of RS code and LDPC code is shown in Fig.6.

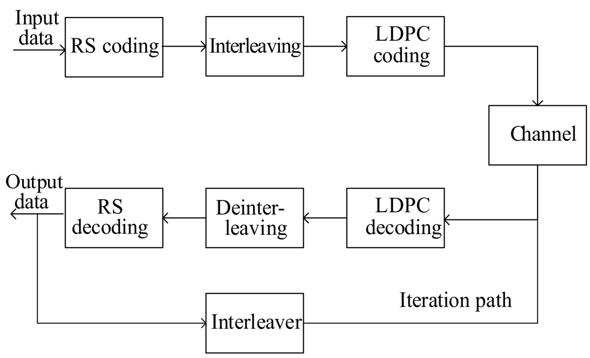

Fig.6 Cascade code design block diagram

When optimizing the FEC technology in OTN, we use RS(255,239) code as the outer code, while the pattern selection of the inner code LDPC needs to be further analyzed. Below, we will analyze the performance of LDPC code in cascaded code from the three aspects of code length, code rate and iteration times.

First of all, we will analyze the performance impact of FEC technology in OTN using cascaded code with outer code of RS(255,239) code and inner code of LDPC code of different code lengths. The simulation is carried out under the additive white Gaussian noise (AWGN) channel. The modulation method uses binary phase shift keying

(BPSK). The cascade code uses RS(255,239) code and LDPC code to cascade. The bit rate of the LDPC code is 0.5, the number of iterations is 30, and the code length is 576, 1 248 and 2 016, respectively. Fig.7 shows that in OTN, the performance comparison of cascaded codes with LDPC codes of different code lengths is selected.

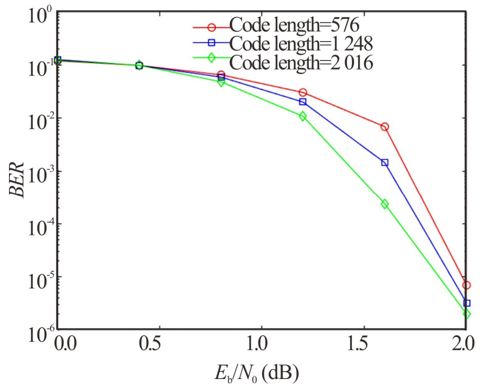

Fig.7 Performance comparison of LDPC codes with different code lengths in cascaded codes

As can be seen from the simulation results in Fig.7, under the same signal-to-noise ratio, as the LDPC code length increases, the performance of RS(255,239)+ LDPC cascade code increases. When the signal-to-noise ratio is not high, that is, the signal-to-noise ratio is less than 1.2 dB, there is almost no difference in the performance of the LDPC code of the three code lengths. The increase in code length does not improve the OTN's error performance much, but with the increase of the signal-to-noise ratio, especially after the signal-to-noise ratio is greater than 1.5 dB, the system's error performance is greatly improved. When the *BER* is 10^{-3}, the LDPC code with a code length of 2 016 and 1 248 is lower than the LDPC code with a code length of 576, and the signal-to-noise ratio is reduced by about 0.4 dB and 0.3 dB, respectively. This shows that with the increase of LDPC code length, the performance of cascaded code will be improved, but the performance cannot be infinitely improved. When the LDPC code length reaches a certain length, the improvement of the error will be smaller and smaller. At the same time, the increase in code length will also make the coding algorithm more and more complex, and the performance will be closer to the limit. Therefore, the increase in LDPC code length within a certain range can improve the error performance.

Secondly, we will analyze the performance impact of FEC technology in OTN using the outer code as RS(255,239) code, while the inner code uses the cascaded code of LDPC code with different bit rates. The cascade code uses RS(255,239) code and LDPC code to cascade. Among them, the code length of the LDPC code is 576, the number of iterations is 10, and the bit rate is 0.5, 0.67 and 0.75, respectively. Fig.8 shows that in OTN, the performance comparison of cascaded codes with LDPC codes with different bit rates is selected.

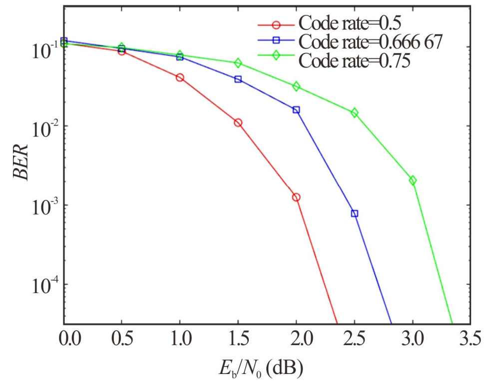

Fig.8 Performance comparison of LDPC codes with different code rates in cascaded codes

As can be seen from the simulation results in Fig.8, under the same signal-to-noise ratio, as the LDPC code rate increases, the performance of RS(255,239)+LDPC cascade code will decrease. In the small signal-to-noise ratio area, that is, when the signal-to-noise ratio is less than 0.5 dB, there is almost no difference in the performance of the LDPC codes of the three bit rates, but after the signal-to-noise ratio is greater than 1 dB, the performance of the LDPC codes with a bit rate of 0.5 begins to be better than that of the other two bit rates, and as the signal-to-noise ratio increases, the smaller the bit rate of the LDPC code, the greater the improvement in the bit error performance of the OTN. When the *BER* is 10^{-3}, the LDPC code with a bit rate of 0.5 is better than the LDPC code with a bit rate of 0.67 and 0.75, and the performance is improved by about 0.3 dB and 0.7 dB, respectively. This shows that as the LDPC code bit rate increases, the performance of cascaded code will decrease.

Finally, we will analyze the performance impact of FEC technology in OTN using the outer code as RS(255,239) code, while the inner code is used as a cascade code of LDPC codes with different iterations. The cascade code uses RS(255,239) code and LDPC code to cascade. Among them, the code length of the LDPC code is 576, the bit rate is 0.5, and the number of iterations is 2, 10 and 50, respectively. Fig.9 shows that in OTN, the performance comparison of cascaded codes with LDPC codes with different iterations is selected.

As can be seen from the simulation results in Fig.9, the performance of RS(255,239)+LDPC cascade code has improved due to the increase in the number of iterations under the same signal-to-noise ratio. When the *BER* is 10^{-2}, the performance of LDPC codes with iterations of 50 and 10 is significantly better than that of LDPC codes with iterations of 2, and the performance of codes with iterations of 50 is approximately 0.2 dB higher than that of codes with iterations of 10. However, the improvement of error performance is limited. With the increase of the number of LDPC decoding iterations, the error performance cannot be improved infinitely. When a certain number of iterations are achieved, it not only increases the complexity of the system and the transmission delay, but the error performance will not be greatly improved.

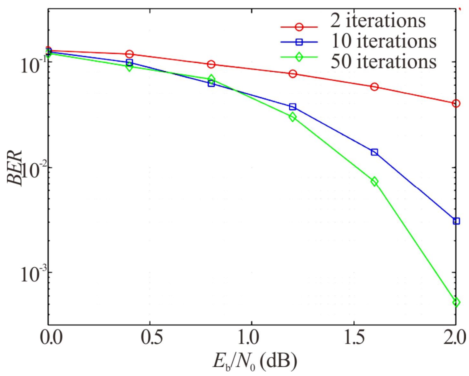

Fig.9 Comparison of the performance of LDPC codes with different iterations in cascaded codes

In the end, we selected the LDPC code with code length N=1 248, bit rate R=0.5, and decoding iteration number of 50, that is, the LDPC(1 248,624) code was used as the inner code of the RS-LDPC cascade code, while the outer code used RS(255,239) code for the cascade design, and it was applied to the OTN to compare and analyze its performance. Fig.10 shows the use of improved cascaded FEC technology in OTN, that is, the use of RS(255,239)+LDPC coding algorithm, compared with the error correction performance of standard FEC technology and unused FEC technology in OTN.

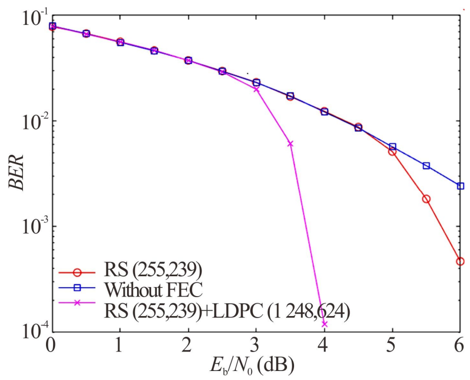

Fig.10 Simulation results of improved FEC technology in OTN

It can be seen from the simulation diagram that under the same signal-to-noise ratio, the performance of the improved cascaded FEC technology is better than the performance of the standard FEC technology. When the signal-to-noise ratio is greater than 3 dB, the performance of the improved cascade FEC technology using RS(255,239)+LDPC(1 248,624) code begins to be better than that of the standard FEC technology, and with the increase of the signal-to-noise ratio, the error improvement is greatly improved. From the vertical view in Fig.10, it can be seen that when the *BER* is 10^{-3}, compared with the standard FEC technology, the *BER* performance of the improved cascaded FEC technology is approximately 1.7 dB higher.

In this paper, we mainly research the FEC technology in OTN. For OTN data frames, the standard FEC technology based on RS(255,239) code is studied, and the data interleaving process and coding algorithm are analyzed. Since the performance of LDPC code is close to the Shannon limit, it is suitable for large-capacity and high-speed transmission systems. On the basis of standard FEC technology, the third-generation FEC technology based on LDPC code is further studied, and an improved FEC technology for cascading RS code and LDPC code is proposed. The outer code is RS code and the inner code is LDPC code. The simulation results show that its performance is improved compared to standard FEC technology.

Ethics declarations

Conflicts of interest

The authors declare no conflict of interest.

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