Comparative analysis on the performance of two concatenated codes for high-speed long-haul optical communication systems*

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(Received 7 March 2012)

After the development trend of high-speed long-haul optical communication systems and the theory of the concatenated code are analyzed, the comparative researches on the performances of the two concatenated codes of the inner-outer type and the improved interleaving type are performed in detail. The theoretical analyses and simulation results show that the inner-outer type concatenated code has the greater redundancy, and the improved interleaving type concatenated code is a superior concatenated code with the advantages of the better error correction performance, moderate redundancy and easy implementation. As a result, the improved interleaving type concatenated code can be better used in high-speed long-haul optical communication systems.

Document code: A **Article ID:** 1673-1905(2012)05-0359-4

DOI 10.1007/s11801-012-2016-0

The state-of-the-art optical communication systems standardized by the ITU employ the concatenated Bose-Chaudhuri-Hocquenghen (BCH) and Reed-Solomon (RS) codes[1,2]. With the development of optical communication systems toward longer distance, larger capacity and higher bit rate, forward error correction (FEC) becomes the first choice to improve the systems performance, because the FEC can gain a much larger transmission distance and make the system more robust under worse conditions[3-7]. Therefore, the FEC technique has been used for compensating the optical transmission quality degradation from noise and pulse distortion in optical communication systems. In particular, the RS(255,239) code is now commonly used and standardized in ITU-T G.975[8] and G.709[9]. Recently, more powerful FEC codes have become necessary to compensate the serious transmission quality degradation. The concatenated code has very powerful performance on outburst error correction and random error correction[10-12], and its net coding gain (NCG) is more superior than that of the single code[11-14]. Furthermore, the concatenated coding scheme is very powerful and effective in optical communication systems[6,11,15,16], so the concatenated code is the main research object of the high-efficiency code for optical communication systems.

Based on the reasons above, the simulation analyses on the performance of two concatenated codes of the inner-outer type and the improved interleaving type for optical communication systems are studied in this paper.

The concatenated code is proposed as a practical method to construct the code with the longer codeword length and the better error correction performance, and it is a special method that a long code can be composed of some short codes. In fact, the most practical concatenated code is the code constructed by the two codes[10,11].

According to the channel coding theorem, the error probability in the decoding process tends to zero at the exponent mode when the codeword length increases[11]. Therefore, the longer codeword must be used for improving the error correction performance of the FEC code. However, the code rate decreases with the increase of the codeword length, accordingly the complexity and calculated amount of the decoding devices increase, so it is difficult to implement. The coding scheme of inner-outer type concatenated code can solve this contradiction correspondingly. The inner-outer concatenated code is the concatenated code applying the inner code and

* This work has been supported by the National Natural Science Foundation of China (Nos.61071117 and 61003256), the Natural Science Foundation of CQ CSTC (No.2010BB2409), and the Science and Technology Foundation of Chongqing Municipal Education Commission (No.KJ110519).

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outer code in series. The encoding process in this coding scheme is divided into two inner-outer serial stages, and the requirement of the codeword length for the channel error correction can be met without increasing the complexity of the encoding/decoding process[11]. A theoretical block diagram of the inner-outer type concatenated code is shown in Fig.1.

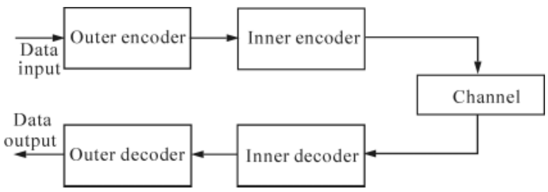

Fig.1 Theoretical block diagram of the inner-outer type concatenated code

If the inner code and the outer code are concatenated directly, the data flow from the inner decoder enters the outer decoder directly. In case that there are some outburst errors in the data flow, it is very likely that the outer decoder can not correct the outburst errors. But the added interleaver can interleave the data in different blocks to get the new data flow, which is then sent into the outer decoder, so the method can avoid the occurrence of certain uncorrectable outburst errors. And the bit error rate (BER) can gradually decrease with the increase of the iteration times by applying the iterative decoding. The theoretical block diagram of the improved interleaving type concatenated code is shown in Fig.2.

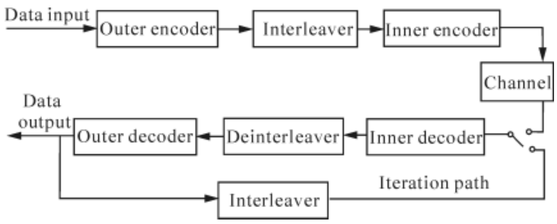

Fig.2 Theoretical block diagram of the improved concatenated code with interleavers

When encoding, the k_1k_2 information elements are first sent into the outer encoder, and the outer encoder can encode the k_1k_2 information elements into k_1n_2 information elements according to its encoding rule. Then the k_1n_2 information elements are sent into the interleaver, and they are sent into the inner encoder after interleaved. The inner encoder encodes the k_1n_2 information elements according to its encoding rule, and then outputs the n_1n_2 code elements. Thus, in the whole course of the encoding, the encoder of the concatenated code inputs the k_1k_2 information elements, outputs the n_1n_2 code elements, and produces the codeword of $[n_1n_2, k_1k_2, d_1d_2]$ concatenated code. Its code rate is $R=(k_1/n_1)\times(k_2/n_2)=R_1R_2$, and its minimum distance is d_1d_2 at least. It is obvious that it is the same as the conventional concatenated code basically, just adding the interleaver in it.

When decoding, the received n_1n_2 code elements are sent into the inner encoder, which can get the k_1n_2 information elements according to the decoding rule of the inner code. The k_1n_2 information elements are sent into the deinterleaver to be deinterleaved according to the reverse interleaving rule of the interleaver, thus the k_1n_2 code elements to be sent into the outer decoder can be got, and the outer decoder decodes the input k_1n_2 code elements to get the k_1k_2 information elements in the terminal of signal source. If the iterative decoding is applied, it is necessary that the n_1n_2 code elements, corresponding to the k_1k_2 information elements which are derived from the previous decoding and got together from the decoding of the inner decoder and outer decoder, are repeatedly sent into the inner decoder and outer decoder to implement the decoding operation as the previous decoding operation after they are interleaved through the interleaver. Thus, a time iterative decoding process is achieved.

The inner code can correct a small quantity of random errors in the channel by using the concatenated code. And when the outburst error or the random error is so much and beyond the error correction capability of the inner code, the inner decoder can produce wrong decoding, and the output codeword can contain the error code. However, it merely corresponds to a few error code elements in the outer code, and can be easily corrected by the outer decoder. Thus the concatenated code is good for the correction of the combined channel error and the relatively long outburst error. Furthermore, the implementation of its encoding/decoding circuit is simple, and it costs less. Therefore, it is more suitable for applying the concatenated code in optical communication systems.

In the inner-outer concatenated codes, the inner code may be binary BCH code, and the outer code may be multiple RS code. The FEC code of this serial concatenated coding scheme with the inner code and outer code can theoretically provide more advantages than the single RS code or single BCH code.

Here, we concatenate the RS(239,223) with BCH(255, 239) and RS(127,119) with BCH(15,7) together to research inner-outer concatenated codes. Choose different SNR values to simulate the two inner-outer concatenated codes, the different BER data can be acquired, and the simulation results compared with that of the RS(255,239) code are shown in Fig.3.

From the error correction performance of the several codes shown in Fig.3, it can be seen that the performance of RS(127,119) + BCH(15,7) concatenated code is very good, compared with the system without FEC code, and its NCG is almost 8.6 dB. RS(239,223)+BCH(255,239) concatenated code also has the NCG of almost 5.16 dB. Thus the error correction performance of the inner-outer concatenated code is significantly superior. But the overhead of RS(127,119)+ BCH(15,7) concatenated code can not be accepted in the optical communication systems for its redundancy of even 128.7%. Though RS(239,223)+BCH(225,239) concatenated code has the redundancy of 14.35%, this code limits the improvement of error correction performance, and is less practical than the single RS(235,239) code which only has the redundancy of 6.69%. So RS(239,223)+BCH(225,239) concatenated code is not definitive in its prospect of the practical application.

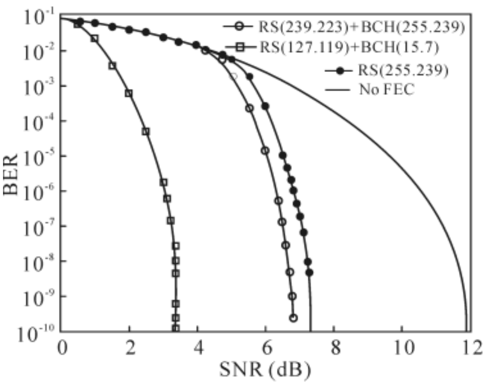

Fig.3 Simulation results of the inner-outer type concatenated codes

Due to the particularities of high-speed optical communication, superior error correction capabilities should be required, and the complex device can be arisen from the complex encoding-decoding circuits. We consider that the qualities of optical communications can be further improved by applying the concatenated code and the interleaved code combined with the classic RS code or BCH code together, and the more practical and realtime encoding/decoding is applied in long-haul optical communications by designing some novel concatenated coding schemes. Because there are some problems on the considerably complex encoding/decoding and the implementation of the parallel-concatenated coding scheme, we assume that the encoding is performed twice for the information directly, but this way isn't applied in the parallel-concatenated coding scheme. The data are encoded again after performing encoding once, thus there is a larger probability to correct the error. However, based on the data after encoding, it isn't obvious to improve the performances by directly performing encoding again. Therefore, we think that the data are encoded again after the data from the first encoder are interleaved by the interleaved code scheme, and thus there are chances to both further improve the error correction performance of the system and considerably enhance the capability of outburst error correction. The considered coding scheme is shown in Fig.2.

In fact, the interleaving type concatenated coding scheme is slightly different from the inner-outer concatenated coding scheme in Fig.1. Firstly, the information is encoded once, then a matrix interleaving is performed, the encoding is carried out once again, and finally the decoding is implemented twice according to the sequence of the data. Thus, there are chances not only to check more errors theoretically but also to solve the outburst error more effectively in optical communication channels, because the interleaving type concatenated code after interleaving the RS code can have more effective outburst error correction performance. The most important one is that the encoding/decoding structures of the interleaving type concatenated coding scheme are very simple, the existing RS code and BCH code can be applied, and the soft encoding/decoding scheme isn't necessary. Thus, it is possible to implement the interleaving type concatenated code, which is suitable for the special optical communication transmission media. In theory, the interleaving type concatenated codes can provide more effective error correction performance, because the interleaved codes are introduced and they can improve the outburst error correction capabilities. Therefore, the interleaving type concatenated code is theoretically a more effective and feasible code structure and a very good FEC coding scheme.

To implement the interleaving type concatenated code, RS(239,223) code and RS(255,239) code are respectively concatenated together with BCH(255,239) and RS(255,223) as Fig.2. After the different SNR (i.e., EbN0) parameters are set in the additive white Gaussian noise (AWGN) channel of the interleaving type concatenated code, the BER results of the RS(239,223)*BCH(255,239) interleaving type concatenated code and the RS(255,239)*RS(255,223) interleaving type concatenated code are separately tested. The simulation results compared with that of the inner-outer type concatenated code and the RS(255,239) code are shown in Fig.4.

From Fig.4, it can be seen that RS(255,239)*RS(255,223) interleaving type concatenated code can almost gain the NCG of 6.9 dB compared with the system without FEC code at the BER of 10^{-10}. Although the NCG of this code is 1.7 dB less than that of RS(127,119)+BCH(15,7) inner-outer type concatenated code, this code has the lower redundancy of only about 17.22%. From this point, RS(255,239)*RS(255,223) interleaving type concatenated code has more advantages than RS(127,119)+BCH(15,7) inner-outer type concatenated code. The NCGs of RS(239,223)*BCH(255,239) interleaving type concatenated code with the redundancy of 14.35% and RS (255,239)*RS(255,223) interleaving type concatenated code are respectively greater by about 1.5 dB and 2.3 dB than that of RS(239,223) + BCH(255,239) inner-outer type concatenated code. Thus considering the integrated redundancy and error correction performance, the improved interleaving type concatenated code is more suitable for optical communication systems than the inner-outer type concatenated code.

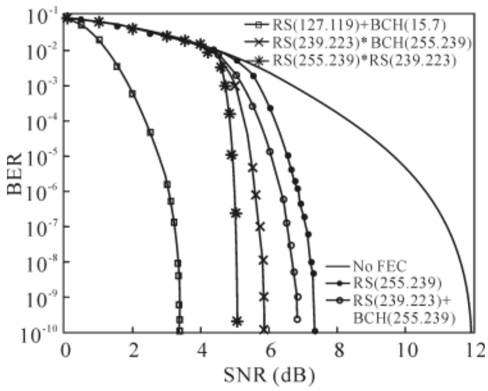

Fig.4 Comparative simulation results for the improved interleaving type concatenated codes

The performance analyses of the two schemes of the inner-outer type concatenated code and the improved interleaving type concatenated code for high-speed long-haul optical communication systems are performed in this paper. The comprehensive analyses show that the inner-outer type concatenated code has greater redundancy while the improved interleaving type concatenated code is a better one with the advantages of higher error correction performance, moderate redundancy and easy implementation. So the improved interleaving type concatenated code can be better used in high-speed long-haul optical communication systems.

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