Performance of CO-OFDM system with RS-Turbo concatenated code*

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In this paper, the RS-Turbo concatenated code is applied to coherent optical orthogonal frequency division multiplexing (CO-OFDM) system. RS(186,166,8) and Turbo code with code rate of 1/2 are employed for RS-Turbo concatenated code. Two decoding algorithms, which are Max-Log-MAP algorithm and Log-MAP algorithm, are adopted for Turbo decoding, and the iteration Berlekamp-Massey (BM) algorithm is adopted for RS decoding. The simulation results show that the bit error rate (*BER*) performance of CO-OFDM system with RS-Turbo concatenated code is significantly improved at high optical signal to noise ratio (*OSNR*), and the iteration number is reduced compared with that of the Turbo coded system. Furthermore, when the Max-Log-MAP algorithm is adopted for Turbo decoding, the transmission distance of CO-OFDM system with RS-Turbo concatenated code can reach about 400 km without error, while that of the Turbo coded system can only reach about 240 km when *BER* is lower than 10^{-4} order of magnitude.

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Coherent optical orthogonal frequency division multiplexing (CO-OFDM) has been widely investigated as a promising technology for next generation high-speed optical transmission systems because of its good properties, such as high spectral efficiencies, robustness against chromatic dispersion and good compatibility with WDM systems[1]. Currently, the research about CO-OFDM system is mainly focused on spectral efficiency, channel estimation, and fiber nonlinearity[2-4]. The bit error rate (*BER*) performance of CO-OFDM system is significantly deteriorated because of the existence of fiber nonlinearity. Nowadays, methods against the fiber nonlinearity include new modulation formats, channel coding and so on[5,6].

In recent years, Turbo code and low-density parity-check (LDPC) code have attracted a growing interest as the 3th generation of the forward error correction (FEC) standard in contemporary fiber-optic transmission systems. LDPC code is widely used in high-speed long-haul CO-OFDM systems[7-10].

Turbo code has strong error correction capability, and its error correction performance is near the Shannon limit[11]. However, Turbo code is rarely applied in CO-OFDM system[12]. In this paper, Turbo code is employed in CO-OFDM system. The *BER* performance is analyzed by simulation. However, the existence of "error floor" at high signal to noise ratio (*SNR*), which is due to the relatively low weight of the code, makes it hard to decrease the *BER* of Turbo code, when the *BER* is smaller than a certain degree[13]. As a result, the application of Turbo code is limited because of the "error floor" phenomenon. Studies show that the "error floor" phenomenon can be improved by using concatenated code[14]. So RS-Turbo concatenated code is designed in this paper, which includes RS code (186,166,8) and Turbo code. The simulation results show that the "error floor" phenomenon is eliminated and the *BER* performance is improved in three aspects, which are *OSNR*, iteration number and transmission distance.

The scheme of RS-Turbo concatenated code is shown in Fig.1. It consists of RS outer code followed by a Turbo inner code[15].

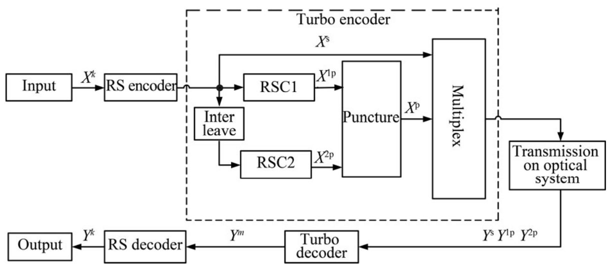

Fig.1 Principle structure of RS-Turbo encoding and decoding

Input data are encoded by RS encoder for X^s, then the sequence X^s is divided into 3 ways for Turbo encoding.

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The first way keeps the original sequence X^s unchanged, the second way generates check bits X^{1p} by RSC1 encoder, and the last way which is interleaved generates check bits X^{2p} by RSC2 encoder. In order to improve the code rate, the check sequences X^{1p} and X^{2p} are put into the puncturing device, then the last check bits sequence X^p is generated by deleting some check bits from two check sequences periodically. At last, the RS-Turbo encoding is completed by multiplexing. The Turbo code with code rate of 1/2 and the shortened RS code (246,226,8) are employed in this paper.

The algorithms of RS-Turbo code can be separated into two classes. The completely iterative decoding algorithm iterates back and forth between the Turbo decoder and the RS decoder. Partially iterative decoding algorithm does not iterate between the Turbo decoder and the RS decoder. Iterative decoding may still take place within the Turbo decoder and also within the RS decoder. However, there is no exchange of information from the RS decoder to the Turbo decoder in partially iterative decoding algorithm. Compared with the completely iterative decoding algorithm, the partially iterative decoding algorithm gets less complexity and smaller time delay, so it is employed in this paper. In this decoding algorithm, two improved iterative MAP decoding algorithms are employed for the Turbo code, which are Log-MAP and Max-Log-MAP[16]. The hard outputs of the Turbo code are the inputs of an RS decoder using iterative BM decoding algorithm.

The functional block diagram of the CO-OFDM system is shown as Fig.2.

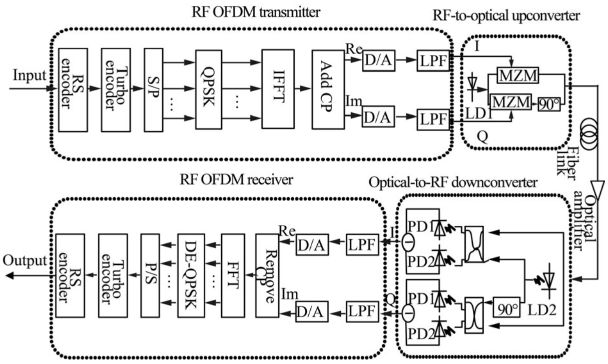

Fig.2 Functional block diagram of CO-OFDM system

The CO-OFDM system can be divided into five parts: RF OFDM transmitter, RF-to-optical upconverter, fiber link, optical-to-RF downconverter and RF OFDM receiver. In the part of RF OFDM transmitter, the data are firstly generated with a Matlab program, which are subsequently encoded by RS-Turbo, modulated with QPSK, converted into time domain using IFFT, and inserted with cyclic prefix[17].

In the part of RF-to-optical upconverter, two Mach Zehnder modulators (MZMs) are used in I/Q modulation for RF-to-optical upconversion, with real/imaginary part of the OFDM signal fed into real/imaginary arm of the optical modulator.

In the part of fiber link, the optical OFDM signal is then fed into a recirculation loop which includes four spans of 80 km standard single mode fiber (SSMF) and an erbium-doped fiber amplifier (EDFA) to compensate the loss.

In the part of optical-to-RF downconverter, the output optical signal from the loop is fed into an OFDM optical-to-RF downconverter that includes two balanced receivers and one local laser.

In the part of RF OFDM receiver, the RF signal is then fed into RF OFDM receiver for signal processing. The OFDM receiver signal processing involves analog-to-digital conversion, removing cyclic prefix, fast Fourier transform (FFT), base-band signal demodulation and RS-Turbo decoding. At last, the output data are obtained.

Tab.1 gives the simulation parameters. Two simulation softwares, which are Matlab and Optisystem, are used in the system.

Tab.1 Parameters used in the simulation

Parameter	Setting
Sub-carrier	512
Number of OFDM symbols	200
Format of digital mapping	QPSK
Format of code	Turbo code (code rate of 1/2), RS code (186,166,8)
Bit rate	50 Gbit/s, 22 Gbit/s
Sequence length	131 072
Interleaving format	Random interleaving
Decoding algorithm	Log-MAP, Max-Log-MAP, BM
Number of FFTs	512
Length of cyclic prefix	64
CD coefficient of fiber	16.75 $ps\cdot nm^{-1}\cdot km^{-1}$
Differential group delay	0.2 ps/km
Dark current of PD	10 nA
Gain of optical amplifier	16 dB
Noise figure	3.2 dB
Attenuation coefficient of SMMF	0.2 dB/km

Program simulation is in accordance with the above implementation structure in Matlab. We compared the performance between the Turbo code and the RS-Turbo concatenated code in CO-OFDM system by simulation[18]. Matlab is used for processing signals and Optisystem is used for building the CO-OFDM system. Through the simulation results, the performance of CO-OFDM system using RS-Turbo concatenated code is analyzed in three aspects.

The *BER* performances of CO-OFDM system using RS-Turbo concatenated code and Turbo code for different *OSNRs* are shown in Fig.3. Max-Log-MAP algorithm and Log-MAP algorithm with 3 iterations are adopted for Turbo decoding in the simulation. When *OSNR* is greater than 18 dB, the RS-Turbo concatenated code with Max-Log-MAP algorithm gets the best *BER* performance, and it can implement error-free transmission. RS-Turbo concatenated code with Log-MAP algorithm and Turbo code with Log-MAP algorithm get similar *BER* performance, and they can both implement error-free transmission with *OSNR* exceeding 20 dB. Turbo code with Max-Log-MAP algorithm cannot implement error-free transmission within *OSNR* of 30 dB, and the "error floor" phenomenon appears when *OSNR* is greater than 22 dB. We can see that the *BER* cannot be decreased with the increasing of *OSNR*. The *BER* of the uncoded system can only reach the order of magnitude of 10^{-2}. The *BER* performance of coded system is significantly improved compared with the uncoded system. The *BER* performance of RS-Turbo concatenated code can reach error-free transmission within *OSNR* of 18 dB, while 20 dB for Turbo code. RS-Turbo coded system can achieve about 2 dB gain compared with the Turbo coded system. We can also find that the "error floor" phenomenon is eliminated by using RS-Turbo concatenated code.

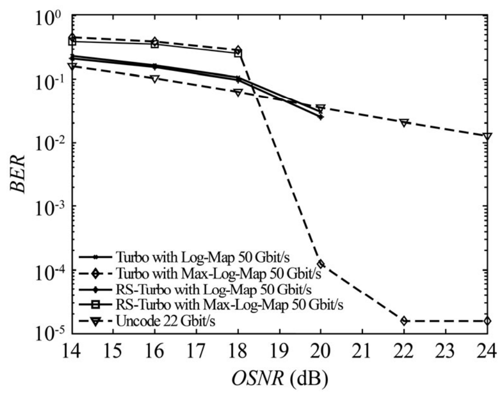

Fig.3 *BER* performance comparison between RS-Turbo code and Turbo code

The relationship between iteration number and *BER* is shown as Fig.4. The simulation parameters are set as follows: transmission rate is 50 Gbit/s, *OSNR* is 20 dB, and transmission distance is 240 km. In this simulation, Max-Log-MAP decoding algorithm is employed. From the simulation results we can see that the *BER* performance of the CO-OFDM system with RS-Turbo concatenated code is significantly improved compared with that of Turbo coded system in the same number of iterations. After 3 iterations, the *BER* is reduced to zero for RS-Turbo concatenated code, because the error occurrence for Turbo code is within the capability of RS code. When the iteration number is increased to 5, the *BER* reaches the order of magnitude of 10^{-4}, and it cannot make an obvious improvement to increase the iteration number for Turbo code. Therefore, adding the RS code can reduce the iteration number and eliminate the "error floor" phenomenon.

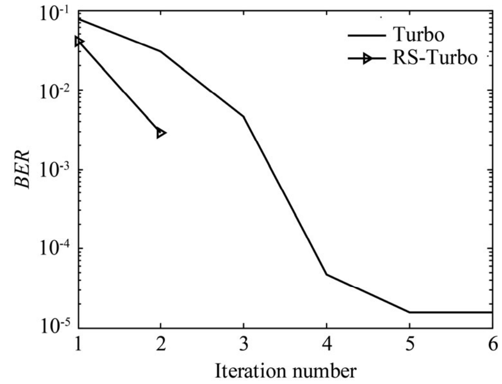

Fig.4 *BER* performance comparison for different iteration numbers

With transmission rate of 50 Gbit/s, *OSNR* of 21 dB and 3 iterations, the *BER* performances of CO-OFDM system using RS-Turbo concatenated code and Turbo code for different transmission distances are shown in Fig.5. When the transmission distance is less than 400 km, the CO-OFDM system with RS-Turbo concatenated code gets much better *BER* performance than that with Turbo code. The CO-OFDM system with RS-Turbo concatenated code can transmit about 400 km without error, while the *BER* of Turbo coded system can only reach the order of magnitude of 10^{-4} within 240 km. For uncoded system with transmission rate of 22 Gbit/s, the *BER* is greater than the order of magnitude of 10^{-2} when the transmission distance exceeds 80 km. The transmission distance of CO-OFDM system with RS-Turbo concatenated code can reach about 400 km without error, while that of Turbo coded system can only reach about 240 km when *BER* is lower than the order of magnitude of 10^{-4}. Therefore, the transmission distance is significantly improved by using RS-Turbo concatenated code.

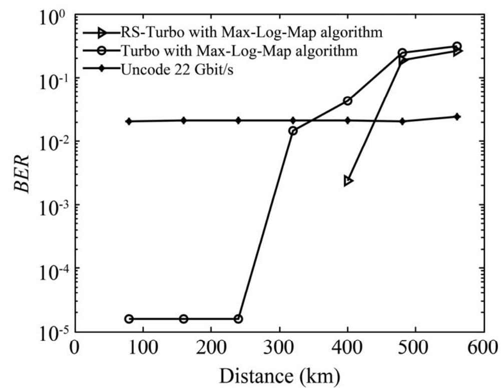

Fig.5 *BER* performance comparison for different transmission distances

In this paper, the RS-Turbo concatenated code is applied to the CO-OFDM system and compared with Turbo coded system. From the simulation results, we can come to a conclusion that the system with RS-Turbo concatenated code needs lower *OSNR* at the same *BER* compared with the Turbo coded system. The *BER* performance of RS-Turbo concatenated code can reach error-free transmission within *OSNR* of 18 dB, while 20 dB for Turbo code. The RS-Turbo coded system can realize about 2 dB gain compared with the Turbo coded system. The RS-Turbo coded system can transmit longer distance at the same *BER*, and it can reach the same *BER* performance with fewer iterations.

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