COL **10**(Suppl.), S20609(2012) CHINESE OPTICS LETTERS December 30, 2012

PMD mitigation by LDPC codes with polarization scramblers

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Received March 30, 2012; accepted June 26, 2012; posted online, 2012

Low-density parity-check (LDPC) codes combined with polarization scramblers are used to mitigate polarization mode dispersion (PMD) in 40-Gb/s optical fiber system. The simulations are performed to compare the correction performance of LDPC codes and Reed–Solomon (RS) code used in this PMD mitigation scheme. Results show that LDPC codes can achieve a better performance than the RS code with the same redundancy. The scrambling speed of polarization scramblers for LDPC codes system is also discussed, and the optimal speed of 10 MHz is obtained.

OCIS codes: 060.2330, 060.4510.
doi: 10.3788/COL201210.S20609.

Polarization mode dispersion (PMD) is one of key factors that limit the performance for high-speed long-haul optical fiber transmission system. Several techniques for PMD compensation or mitigation have been proposed and verified[1−6], such as optical PMD compensator, electronic distortion equalizer, coherent detection with digital signal processing, fast polarization scrambling with forward error correction (FEC), and so on. In this letter, we adopt the method of fast polarization scrambling with FEC to mitigate PMD.

Low-density parity-check (LDPC) codes have become more attractive as FEC codes for high-speed optical communications[5,6]. Instead of using Reed-Solomon (RS) codes in previous literatures, the combination of LDPC codes with polarization scramblers which acts as the solution of PMD mitigation is studied.

Figure 1 illustrates the basic principle of PMD compensation by using polarization scrambler with FEC. For a given FEC, there is a maximum burst-error-correction length (BECL) $t_{\max}$. If the number of error bits exceeds $t_{\max}$, FEC cannot correct all the errors efficiently, for instance, FEC may not be able to correct the errors resulted from abrupt outages events induced by PMD, as shown in Fig. 1(a)[3]. By rapidly scrambling the polarization states over the Poincaré sphere with scramblers, the PMD dynamics is accelerated such that the error counts are essentially equalized and are always well below the BECL and all the errors can be effective corrected by the FEC, as shown in Fig. 1(b). It is the redistribution of instantaneous differential group delay (DGD) to its generic Maxwellian distribution through the polarization scramblers that essentially equalizes the error counts in FEC frames to allow the FEC to be more effective in correcting PMD induced errors.

Here, we adopt irregular LDPC codes. In order to compare with the RS (255, 239) code which is recommended in ITU-TG.975, the redundancy of the LDPC codes is set to 6.67% and interleaving depth is 16. We choose irregular LDPC (2 040, 1 903) codes whose parity-check matrix has a constant column weight of 3 (k=3) and a row weight-mean of 45. The size of a LDPC frame is 16×2 040. The location of "1" in parity-check matrix is generated randomly with a requirement that cycle 4 is avoided. By using the Gaussian elimination, a generating matrix is obtained. For LDPC decoding, sum–product algorithm (SPA) is used[7]. The flat-flow of the decoding process is shown in Fig. 2.

Figure 3 illustrates the schematic of the simulation system. A 42.5-Gb/s non-return to zero differential phased shift keying (NRZ-DPSK) optical fiber transmission system is set up. Transmission link consists of 5 fiber spans, each fiber span is 100 km long and there is a polarization scrambler in front of each span, the PMD coefficient of the fiber is set to $\tau = 0.15$ ps/$\sqrt{\text{km}}$. The polarization scrambler is composed of three cascaded wave-plates with rapidly changing rotation angles and $\lambda/4$, $\lambda/2$, $\lambda/4$ phase retardations, respectively. The receiver is comprised of a one bit-delay interferometer and a balanced detector. A Guassian optical filter before the receiver and fifth-order Bessel electrical filter after the balanced detector are used, whose 3-dB bandwidth are 72 and 26 GHz, respectively. The received electrical data stream is processed by de-interleave and de-coder. In iterative

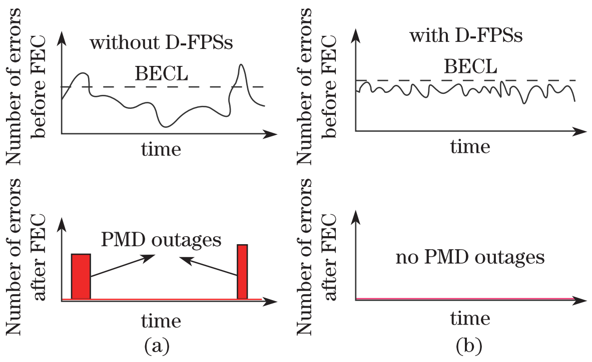

Fig. 1. Number of errors before and after FEC (a) without and (b) with the D-FPSs as a function of time[5].

decoding process, the maximum number of iterations is set to 50.

Scrambling speed of polarization scramblers is an important factor to affect the performance of BER with FEC. According to Ref. [4], the appropriate scrambling speed ranges from B/BECL to $B/8 \cdot d$, where B is the bit rate, BECL is the burst error correctable length of the FEC, and d is the interleaving depth. For RS (255, 239) codes, the interleaving depth is 16 symbols (i.e., 128 bits), the BECL equals 1 024 bits. So the scrambling speed is at least 40 MHz. To compare with RS (255, 239) code, interleaving depth of LDPC (2 040, 1 903) codes is also set to 16. However for LDPC (2 040, 1 903) codes whose error correction performance depends on many factors such as the number of iterations, is hard to work out the BECL precisely. Therefore, a simulation for selecting the optimal scrambling speed is carried out. Figure 4 shows BER performance versus OSNR with the scrambling speeds of 160, 80, 40, 20, 10, and 1 MHz, respectively. Here, we define cut-off OSNR, which corresponds to the value that the BER turns to zero when OSNR exceeds it. The smaller cut-off OSNR is, the better correction performance of FEC codes have. We see that the cut-off OSNRs are 10.9, 10.9, 10.8, 10.6, 10.6, and 10.9 dB corresponding to scrambling speeds from 160 to 1 MHz cases, respectively. The results show that 20 and 10 MHz both can reach a very good BER performance, while a higher (e.g., 160 MHz) or lower scrambling speed (e.g., 1 MHz) will lead to a higher cut-off OSNR. These results are coincident with the experimental result refers to Ref. [6]. In practice, we expect the cut-off OSNR as low as possible. We choose the relatively low speed of 10 MHz as the optimal speed of LDPC (2 040, 1 903) codes for easy implementation in practice.

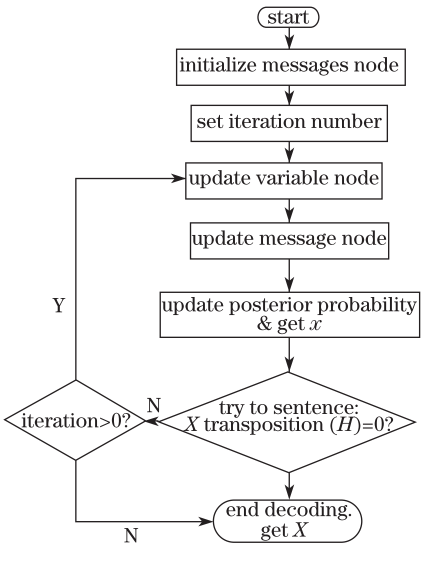

Fig. 2. Flow chart of the decoding process.

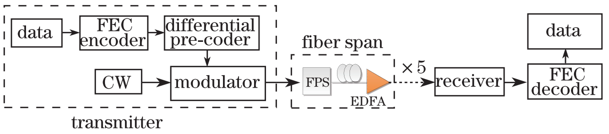

Fig. 3. Simulation system of PMD mitigation with polarization scramblers and FEC for 42.5-Gb/s DPSK modulation format.

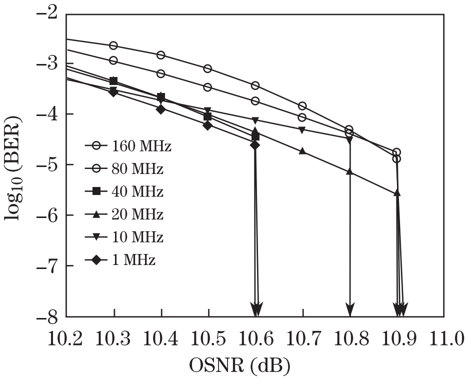

Fig. 4. (Color online) BER versus OSNR with different scrambling speed from 160 to 1 MHz (arrow means when OSNR is over the value, BER turns to zero).

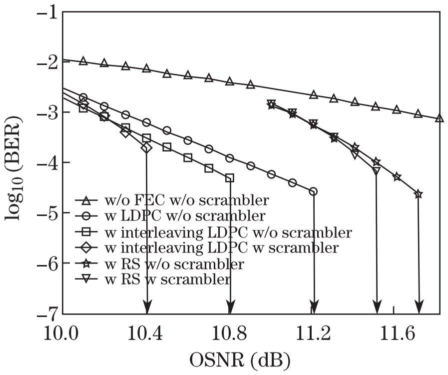

Fig. 5. BER versus OSNR for the systems with LDPC code and RS code.

The error correction characteristics of the different kinds of LDPC (2 040, 1 903) codes and RS (255, 239) codes are investigated. Figure 5 shows the BER performance of several kinds of codes in the transmission system. The chosen scrambling speed for LDPC codes is 10 MHz. We see that for different FEC codes, the cut-off OSNRs are 10.4, 10.8, 11.2, 11.5, and 11.7 dB, respectively. The results show that, LDPC codes have stronger error correction capability than RS codes for the similar redundancy. PMD mitigation performances using polarization scrambler with FEC (either RS codes or LDPC codes) are better than without scramblers. For the polarization scrambler with FEC situations, the requirement of OSNR for the system with LDPC codes is 1.1 dB lower than the system with RS codes. For the cases with and without scramblers, the requirement of OSNR lower 0.4 and 0.2 dB for LDPC and RS codes, respectively. Even the scrambles are absent and without interleaving, LDPC codes have the better correction performance than RS codes combined with polarization scrambler. So we can get the conclusion that, LDPC codes are the good substitute of the RS codes for the PMD mitigation scheme in which the polarization scrambler and FEC are used together.

In conclusion, instead of RS codes, LDPC codes are successfully used with polarization scrambler in the PMD mitigation scheme. The optimal scrambling speed of polarization scrambler for LDPC codes is discussed and obtained by simulation. The effectiveness of the proposed PMD mitigation scheme is verified. Compared with the similar redundancy RS code, LDPC codes have a better performance of error correction capability and lower OSNR requirement. Therefore, LDPC codes are a good substitute of RS codes in the PMD mitigation scheme.

This work was supported by Chinese Universities Scientific Fund under Grant No. BUPT 2011RC009.

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