HIGH BIT RATE MULTI-LEVEL MODULATION AND CODING TECHNOLOGIES FOR 100 GB/S SUBMARINE DWDM OPTICAL COMMUNICATIONS

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Abstract: 100 Gb/s per channel DWDM optical communications are attractive for submarine networks with higher spectral efficiency (e.g. 2 bit/s/Hz) and lower per bit transceiver cost than 40 Gb/s systems. Through simulations we investigate the transmission of 100 Gb/s dual-polarization RZ-QPSK optical signal transmission over transoceanic distances. It poses significant technical challenges to deploy 100 Gb/s systems over transpacific distances with adequate performance margin. We further introduce capacity approaching LDPC-coded multi-level turbo equalization schemes which can offer extra system margin from the FEC coding perspective.

1. INTRODUCTION

In the recent few years, the optical DWDM communications with per-channel bit rate at 100 Gb/s have attracted strong interests, and the terrestrial communication industry is expecting the deployment of 100 Gb/s systems within a few years. With the adoption of advanced multi-level modulation and digital coherent receiving technologies, the demonstrated 100 Gb/s DWDM systems have shown remarkable performance in tolerating some linear detrimental effects during the optical signal transmission, including the fiber chromatic dispersion (CD), polarization mode dispersion (PMD), and narrow band filtering [1-2].

As for the submarine optical communications, 40 Gb/s per channel DWDM systems are expected to have deployment in the very near future, and 100 Gb/s per channel transmissions seem to be the natural next step. Recently, 100 Gb/s per channel DWDM signals were transmitted over 7040 km of large effective area fibers using Raman-assisted Eribium doped fiber amplifiers [3]. Here we will simulate the transmission of 100 Gb/s dual-polarization (DP) RZ-QPSK optical signals over transoceanic distances, and further introduce an advanced capacity approaching low-density-parity-check (LDPC)-coded multi-level turbo equalization scheme which can offer extra system margin from the FEC coding perspective.

2. SYSTEM ARCHITECTURE AND OPERATION PRINCIPLES

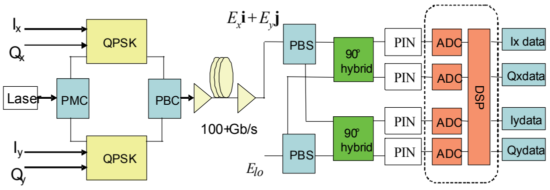
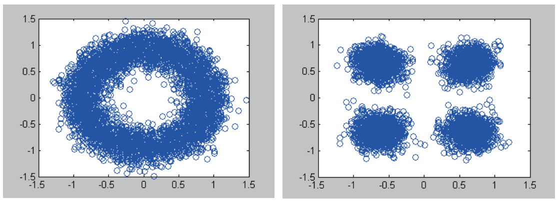


Fig.1 Generic system architecture

Fig. 1 shows the generic system architecture of a dual-polarization QPSK system using coherent detection. At the transmitter side, the source laser is split into two branches by a polarization maintaining coupler and modulated with QPSK modulators using two data streams, at a rate of 25 Gb/s each. The two branches are then recombined by a polarization beam combiner with two orthogonal polarizations to form a total transmission rate of 100 Gb/s. At the receiver end, the signal is split by a polarization beam splitter into two branches, each of which will be detected by a 90°-hybrid coherent receiver and submitted to a DSP unit. The DSP unit in turn will process the received signal to recover the original data.



(a) (b)

Fig.2 Constellations of the received signals with DSP processing (a) after cross-polarization equalization (b) after frequency offset and phase recovery

The DSP is used to compensate the signal distortions, and recover the original signals in two orthogonal polarizations. This is achieved in a multi-stage structure [4]. Following the coherent polarization diversity detection and analog-to-digital converters (ADC), there are four digitalized channels corresponding to the I phase and Q phase of X and Y components. The X and Y components at the receiver side are generally a combination of the X and Y polarization states of the transmitted signal. After the ADC, digital finite impulse response (FIR) [4] or infinite impulse response (IIR) [5] filters are used to compensate the fiber CD dispersion. Following the CD compensation, cross channel/polarization equalization is implemented to separate the two polarization states of the received signal. Due to the randomness of the polarization rotations and PMD effects, the tap coefficients are adaptively updated using the constant modulus algorithm (CMA) [4]. The frequency and phase offsets between the incoming signal and the local oscillation (LO) light in the coherent detection are compensated with carrier phase estimation and compensation modules. In the last stage, the bit stream is recovered through signal demapping and bit decoding. Fig. 2 shows the typical constellations of the received signals after cross-polarization equalization using CMA algorithm and the received signal after frequency offset and phase recovery.

3. SIMULATIONS AND RESULTS

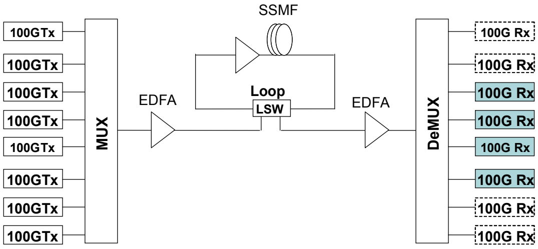


Fig.3 Simulation models

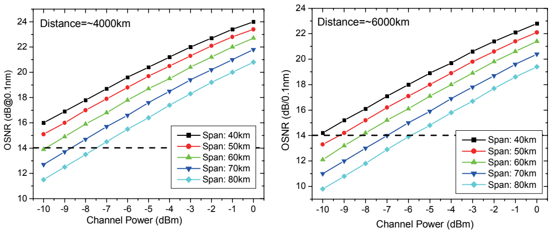
The simulation model is shown in Fig.3. The transmitters are 120 Gb/s (20% overhead for FEC) DP-RZ-QPSK signals with 50% duty cycle. The channel spacing is 50 GHz, and 100 GHz AWGs and a 50 GHz interleaver are used as the optical multiplexer and demultiplexer. In order to make the simulation closer to the real system performance, measurement data of AWGs and interleavers are incorporated in the simulations. The noise figure of the EDFAs used in the transmission link is 4.5 dB. The sensitivity of the receiver is calibrated with some previously published back-to-back experimental results [1]: Bit rate=111Gb/s, BER=1E-3 when OSNR=16.5 dB@0.1nm, and BER=1E-2 when OSNR=13.5 dB@0.1nm. In our simulations, we choose an uncompensated standard single mode fiber link, and the link CD is compensated through the DSP processing at the receiver side. Instead of adopting Raman amplification, we adjust the fiber span length to achieve different transmission link optical signal-to-noise ratios (OSNRs).

The key fiber parameters are based on typical ultra-low-loss standard single mode fibers, and shown in Table 1.

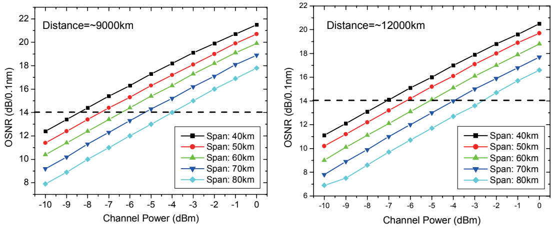
Attenuation	0.18 dB/km
Dispersion	17ps/nm/km
Dispersion slope	0.09 ps/nm^2/km
Core effective area	90 um^2

Table 1 Key fiber parameters (@1550nm) used in the simulation

The OSNR of the transmission link puts an upper bound on the received signal quality. Fig. 4 shows the received signal OSNR under different channel power, total distances and fiber span lengths. When the fiber span length is reduced from 80 km to 40 km, the received signal OSNR can be increased by ~ 4dB @ channel power of -5 dBm. With 20% overhead, advanced FEC schemes can be implemented, and here we choose 1E-2 as the FEC limit. From the back-to-back simulations using our calibrated transmitter and receiver, OSNR of ~14dB@0.1nm is required to achieve BER of 1E-2. A marker line of 14 dB is shown in Fig. 4. For the real system design, longer fiber span lengths are desirable in reducing the transmission link cost.



(a) 4000km **(b)6000km**



(b) 9000km **(d)12000km**

Fig. 4 Received signal OSNR under different channel power and span length

In a dual-polarization digital coherent optical communication system, the DSP at the receiver side has been shown to be effective in compensating the fiber linear distortions, including CD and PMD effects. Although some new algorithms have been proposed to compensate the fiber nonlinearity, their complexity and limited performance improvement in experiments [3] leave fiber nonlinear distortions still a system performance limiting factor in addition to OSNR.

In Fig. 5, the received signal Q factors under span length of 40km are shown. When the total transmission distance is 4000 km and 6000 km, 2.5 dB and 2 dB Q factor margin can be achieved. At transpacific distance of 12000km, the received signal Q factor just reaches the FEC limit.

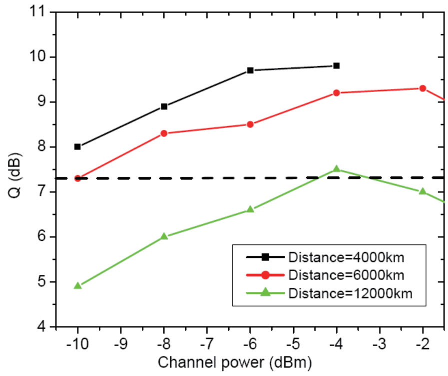


Fig. 5 Received signal Q factors under span length of 40 km.

In order to increase the system Q factor margin for real implementations, there can be some different further approaches: (1) new fiber types, (2) fiber nonlinearity compensation algorithms (3) advanced FEC coding schemes. With some new types of ultra-low-loss and large effective area fibers, the link OSNR can be further increased and the optimal per-channel power can also be increased. Despite the current research efforts in nonlinear compensation algorithms, an effective algorithm with reasonable complexity remains a challenge. With the increasing electronic digital processing capabilities, more sophisticated FEC schemes can be implemented to bring extra system performance margin. In the next session, we will introduce advanced channel capacity approaching coding schemes using LDPC-coded multilevel turbo equalization.

4. ADVANCED CODING SCHEMES

Here we further describe a channel capacity approaching coding scheme. The proposed scheme, shown in Fig. 6, is based on multilevel maximum *a posteriori* probability (MAP) turbo equalization [6]. It is composed of two ingredients: (i) the multilevel BCJR algorithm based equalizer, and (ii) the LDPC decoder. The BCJR equalizer provides soft symbol log-likelihood ratios (LLRs) to the LDPC decoding process. To improve the fiber nonlinearities tolerance, extrinsic LLRs are iterated back and forth between BCJR (MAP) equalizer and LDPC decoder. In [6], with the turbo equalization scheme based on four level BCJR equalizer of memory m=1 and the LDPC(16935,13550) code of girth-10 and column weight 3, we show through simulation that the raw BER of larger than 3E-2 can be reduced to be smaller than 1E-9.

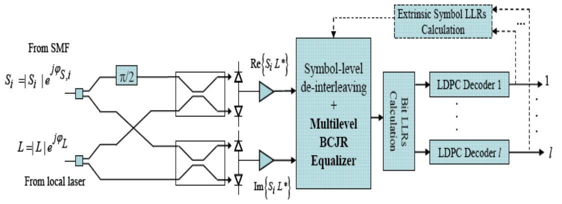


Fig. 6 LDPC-coded multilevel turbo equalization scheme

5. DISCUSSIONS

100 Gb/s per channel DWDM optical communications are attractive with higher spectral efficiency (e.g. 100 Gb/s over 50 GHz channel spacing) and lower per bit transceiver cost than 40 Gb/s systems. However, the commercial deployment of 100 Gb/s systems for transoceanic communications (especially for transpacific distances) imposes some technical challenges. The research progress and the commercialization of some advanced technologies, including new types of optical fiber, innovative DSP algorithms, and advanced FEC coding schemes, will play a crucial role in the future deployment of 100 Gb/s DWDM systems over transpacific distances.

6. REFERENCES

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