Modulation Formats for Ultra Long-Haul Undersea Transmission

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Abstract *This paper reviews recent technology advances in modulation formats including RZ-DQPSK, PDM RZ-DPSK, and offset PDM RZ-DPSK for 40G undersea transmission. Research activities on 100G long-haul transmission are also summarized.*

Introduction

Video (especially high definition video) and P2P (peer-to-peer file sharing) may double IP traffic every two years[1]. To satisfy the demand for capacity, transmission technologies to support higher data rate and higher spectral efficiency are needed. However, the transport of high data rate WDM channels with high spectral efficiency over transoceanic distances requires innovative solutions to numerous technical challenges. These challenges include the nonlinear effects and the increased sensitivity to: accumulated chromatic dispersion, dispersion slope, noise accumulation, and PMD[2]. In order to achieve the same OSNR relative to 10G channels, the launch power of the 40G channel has to be increased by 6 dB to make up for the four times larger signal bandwidth -- this significantly increases nonlinear effects after long-haul transmission. In addition long-haul >40G transmission is more prone to PMD impairments. Therefore, the designed system margin has to be increased to satisfy outage probability.

Advanced modulation formats and detection schemes provide the solution to many of the challenges. Many different modulation formats, that operate with narrow spectral width to maximize spectral efficiency or limit the deleterious effects of fiber nonlinearities or PMD induced penalty, have been investigated. Most recently, coherent detection has generated renewed interest because of its margin advantage over incoherent detection. Since the optimum modulation format and detection scheme is system dependent (dispersion map, transmission distance, channel spacing, repeater spacing, etc), the final choice will typically attempt to maximize system margin and/or reduce system cost.

We review recent laboratory 40G transmission results using advanced modulation formats including: CRZ/PRZ-DQPSK, polarization division multiplexing (PDM) RZ-DPSK, and offset PDM RZ-DPSK. Finally, we discuss modulation formats that could enable submarine systems to operate at data rates exceeding 40G, such as 100G Ethernet.

CRZ/PRZ DQPSK modulation format

To increase system PMD tolerance and spectral efficiency, multilevel modulation formats are attractive because of the lower symbol rate. Multilevel modulation can be achieved with modulation of the amplitude, phase, and polarization, or any combinations of these.

RZ-DQPSK is an example of a multilevel modulation format employing 4-levels of phase modulation[3]. Due to the reduced symbol rate (20GS/s), 40G RZ-DQPSK has much higher tolerance to dispersion, dispersion slope, and PMD compared to 40G DPSK and OOK formats. However, multilevel modulation formats suffer in nonlinear tolerance and OSNR sensitivity, thus limiting the transmission distance. To improve nonlinear tolerance for RZ-DQPSK, bit synchronous polarization (PRZ) or phase[4] (CRZ) modulation can be used. Fig. 1 shows that PRZ and CRZ improved system performance by 1-dB when compared to RZ[5]. CRZ-DQPSK also exhibits low Q-factor fluctuations, and was used to experimentally demonstrate the first 40G trans-Atlantic distance transmission for a multi-level format[5].

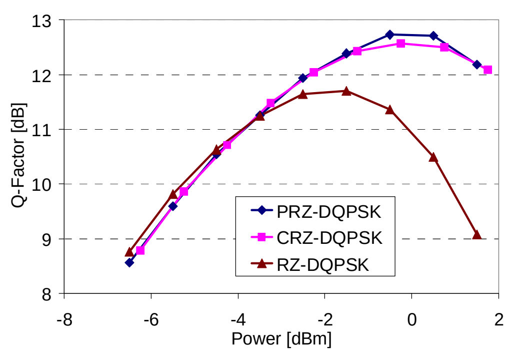

Fig. 1: Chirp (CRZ) and polarization (PRZ) modulation improves nonlinear tolerance of RZ-DQPSK

PDM RZ-DPSK modulation format

Polarization division multiplexing is another approach to lowering symbol rate and increasing spectral efficiency[6]. PDM is realized by transmitting independent information in each of the two orthogonal polarizations. This approach can therefore provide the benefits of DPSK and a lower data rate. 20GS/s PDM RZ-DPSK has superior nonlinear tolerance and similar narrow optical spectrum and dispersion tolerance compared to RZ-DQPSK. Fig. 2 shows PDM improved system performance by 4-dB, compared to RZ-DQPSK[7]. However, an automatic polarization tracking receiver (PTR) is required to demultiplex the two polarization tributaries at the

978-3-8007-3173-2

receiver and PDM is less tolerant to PMD for the same symbol rate.

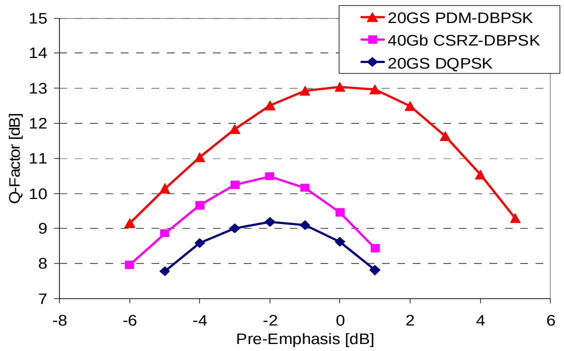

Fig. 2: PDM improves system performance

Offset PDM RZ-DPSK modulation format

Recently, a novel PDM modulation format - offset PDM RZ-DPSK, was proposed in [8]. The expensive automatic PTR is avoided with this format. Non-coherent polarization demultiplexing is achieved with the DPSK demodulator and the balanced detector. The demodulator is biased at transmission maximum for the measurement (signal) polarization, thus a clean open eye is detected for signal polarization after balanced detection (Fig. 3a). On the other hand, the same demodulator is biased at the quadrature point for the orthogonal (crosstalk) polarization due to the ¼R offset. Therefore, the crosstalk polarization is almost completely removed after balanced detection as shown in Fig. 3b. Fig. 3c shows the eye diagram when both signal and crosstalk polarizations are present; clear eye opening exists in the center of the eye thanks to the ½ bit delay between the two polarizations.

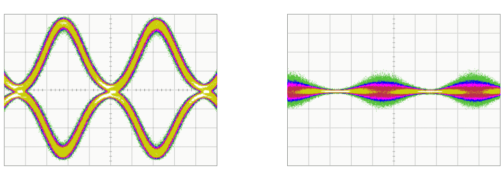

Fig. 3a & 3b: Eye diagram after the balanced receiver of (a) signal polarization only (b) crosstalk polarization only

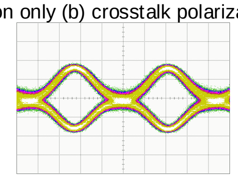

Fig. 3c: Eye diagram of the demultiplexed signal polarization after the balanced receiver

The performance of offset PDM was compared to that of regular PDM under the same conditions (50 x 40Gb/s over 5,200 km with 150 km repeater spacing and 66.6 GHz channel spacing), the long term Q-factor showed similar FEC margin although the average Q-factor was ~1dB worse for offset PDM (Fig. 4). The larger fluctuation of regular PDM RZ-DPSK with automatic PTR may come from weak tracking or loss of control due to the potential existence of "dead spot"

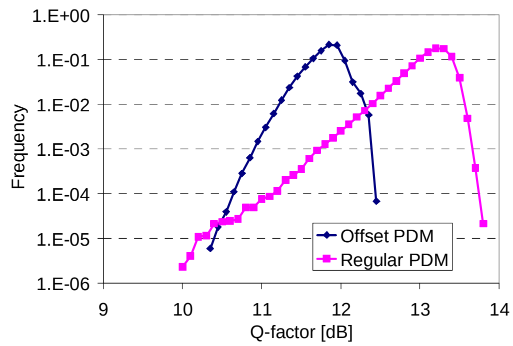

Fig. 4: Long term Q-factor distributions for regular and offset PDM RZ-DPSK after 5,200 km transmission

Modulation formats for 100G

100G transoceanic systems, the submarine industry's most formidable technical challenge, looms on the horizon alongside the promise of compatibility with 100GbE. Among many modulation formats, 25GS/s PDM RZ-QPSK[9,10] and MIMO OFDM[11,12] with digital coherent detection are two formats currently being investigated by many groups. Substantial efforts have been made to transmit 100G WDM channels across transoceanic distances in laboratories[13,14], but with no margin to enable system deployment. Significant and innovative technological advances are needed to enable 100G transmission systems over transoceanic distance.

Conclusions

High data rate transmission in submarine systems is challenging due to nonlinearity and PMD. Modulation formats with better nonlinear and PMD tolerance will be required to keep pace with the increasingly higher data rates and higher spectral efficiency.

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