# Recent advances in undersea long-haul transmission

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**Abstract:** This paper reviews recent technology advances in undersea long-haul transmission including amplification technologies to extend repeater spacing and advanced modulation formats to facilitate higher data rates and improve spectral efficiency.

## Introduction

Internet traffic is growing exponentially fuelled by video applications that consume enormous bandwidth in the core optical networks. To meet the soaring demand for capacity, transmission technologies supporting both higher data rate and higher spectral efficiency with lower cost will be required. One way to reduce the cost of the undersea link is to reduce the number of repeaters (increase repeater spacing), while one way to reduce the cost of terminal equipment is to transmit at higher single channel data rate. This paper reviews recent advances including amplification technologies and advanced modulation formats to extend repeater spacing, facilitate higher data rates, and improve spectral efficiency for undersea long-haul transmission.

## Amplification technologies

Traditionally, undersea systems were designed with simple 980-nm single-stage EDFAs with 45 to 50-km repeater spacing [1]. With the progress in low loss fiber, higher power 980-nm pump, advanced modulation formats and FEC with lower OSNR requirement, the repeater spacing has been stretched to 110-km in the laboratory [2]. The main limitations to further increases in repeater spacing are noise accumulation and gain-limitations for a single-stage EDFA design. To overcome these issues, distributed amplification such as Raman or remote optically pumped EDF amplifiers (ROPA) can be utilized to improve the noise performance of the transmission line [3].

Raman assisted EDFAs (Raman/EDFA) combine distributed Raman pre-amplification with conventional EDFAs [4] to improve noise performance and enable longer spans. Utilization of Raman/EDFAs enabled 150-km repeater spacing with similar performance as that of EDFA-only amplification with 110-km repeater spacing (Fig. 1) [5]. The Raman/EDFA scheme supports a 40 km increase in repeater spacing or equivalently an increase in span loss of approximately 8 dB relative to the conventional EDFA-only scheme.

The ROPA assisted EDFA (ROPA/EDFA) used a section of Erbium inserted ~2/3 into each span and is optically pumped through large effective area fiber to achieve low loss of the remote pump and limit undesired Raman interactions. Compared with Raman/EDFA (Fig. 2), the ROPA/EDFA scheme provided >1-dB OSNR benefit after 11,000-km with 150-km spans [6]. This OSNR improvement resulted in a similar Q-factor enhancement measured using 96x10 Gb/s RZ-DBPSK channels over 9000-km distance.

## Advanced modulation formats

For an existing undersea system, the system aggregate capacity can only be increased by improving spectral efficiency with advanced modulation formats. For new builds, advanced modulation formats can also extend system reach and support higher data rate transmission.

Optical pre-filtering is one of the simplest solutions to achieve high spectral efficiency and its effectiveness has been confirmed by many transmission experiments [6, 7]. In [6], 10G channels spaced 17GHz apart were transmitted through 7300-km enabled by pre-filtering, orthogonal launch and the RZ-DPSK modulation format. Furthermore, pre-filtering reduces signal bandwidth, which increases tolerance to PMD and dispersion slope.

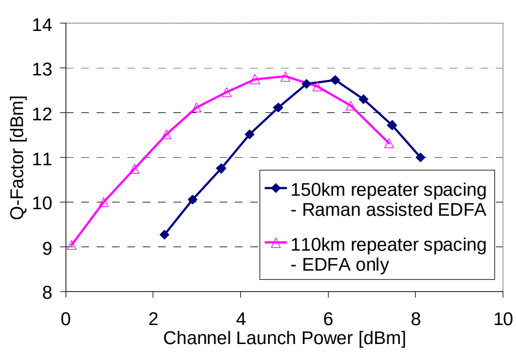


Fig. 1: Comparison of EDFA only vs. Raman/EDFA scheme in 4,450-km 40-Gb/s RZ-DPSK experiment.

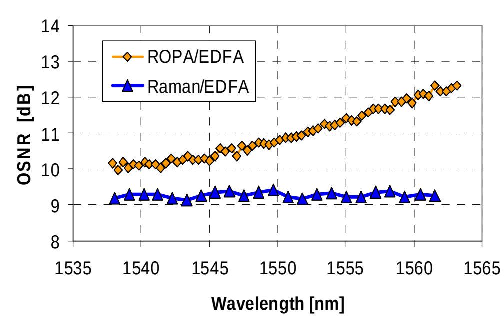


Fig. 2: Received OSNR after 11,000 km transmission with 150 km spans for Raman/EDFA and ROPA/EDFA systems.

To achieve Shannon's capacity for a system, multilevel modulation formats become essential. Due to the lowered symbol rate, multilevel modulation formats improve system chromatic dispersion, dispersion slope and PMD tolerance, which make it more attractive for high data rate transmission. Multilevel modulation can be achieved by modulating amplitude, phase, and/or polarization.

The RZ-DQPSK is an example of a multilevel modulation format employing 4-levels of phase modulation [8]. Due to the reduced symbol rate (20GS/s), 40G RZ-DQPSK has much better tolerance to dispersion, dispersion slope and PMD compared to 40G DBPSK and OOK formats. However, multilevel modulation formats suffer from reduced nonlinear tolerance and OSNR sensitivity, thus limiting the transmission distance.

Polarization division multiplexing (PDM) is yet another approach to lower symbol rate and increase spectral efficiency [9]. PDM is realized by transmitting independent information in each of two orthogonal polarizations. Similar spectral efficiency and dispersion tolerance compared to 40G RZ-DQPSK can be achieved with 40G PDM RZ-DPSK. Furthermore, 40G PDM RZ-DPSK had superior nonlinear tolerance thanks to the RZ-DPSK format. It can therefore support much longer system reach than RZ-DQPSK. Fig. 3 shows PDM improved system performance by 4-dB, compared to RZ-DQPSK [10]. However, an automatic polarization tracking receiver (PTR) with endless control and reset-free operation is required to demultiplex the two polarization tributaries at the receiver. Also PDM is less tolerant to PMD for the same symbol rate.

Recently, a novel PDM modulation format - offset PDM RZ-DPSK, was proposed [11]. The expensive and unreliable automatic PTR is not needed for this format. The incoherent demultiplexing was achieved by the DPSK receiver, to be specific, the orthogonal polarization was suppressed by the DPSK demodulator and balanced detector thanks to the (2n+1)/4 FSR frequency offset (relative to the parallel polarization) and inter-bit delay (½ bit period). The performance of offset PDM was compared to that of regular PDM under the same conditions, the long term Q-factor showed similar FEC margin although the average Q-factor was ~1dB worse for offset PDM (Fig. 4).

**Higher data rate (100G) transmission**

The higher the data rate, the higher the required OSNR. To improve the performance of multilevel modulation format for 100G, coherent detection is preferred to avoid excessive penalties from signal-spontaneous beat noise [12]. The symbol rate will most likely have to be kept below 30G; thus a ≥16-level format is preferred. 25GS/s (28GS/s line rate) PDM RZ-QPSK with coherent detection [13, 14] and MIMO OFDM [15, 16] are two formats currently being investigated by many groups to support 100GbE. Significant and innovative technological advances are needed to facilitate 100G transmission with deployable system margin.

**Conclusions**

Amplification technology has extended repeater spacing from 50 km up to 150 km. Modulation format advances improved spectral efficiency and nonlinear tolerance for undersea systems. Advanced modulation formats with better nonlinear and PMD tolerance will be required to keep pace with the increasingly higher data rates.

**References**


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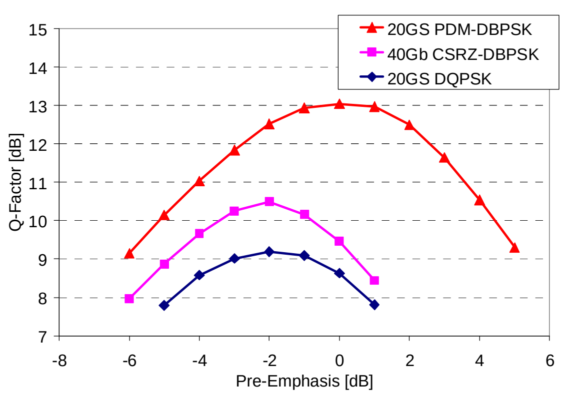


Fig. 3: PDM improves system performance after 5,200 km transmission

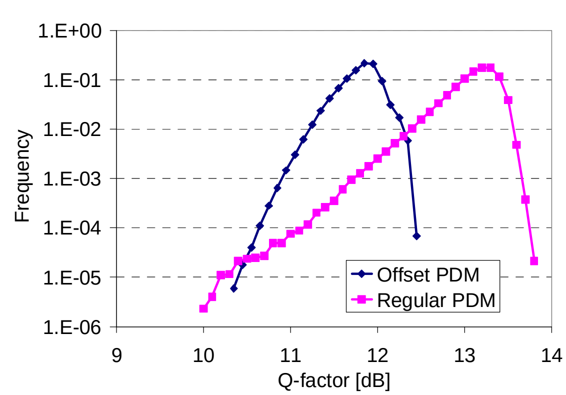


Fig. 4: Long term Q-factor distributions for regular and offset PDM RZ-DPSK after 5,200 km transmission