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125-Gb/s CP-QPSK Field Trial over 4108 km of Installed Submarine Cable

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Abstract: We show the successful transmission of 125-Gb/s CP-QPSK (coherent-detected polarization-multiplexed quadrature phase shift keying) over both 2054 km and 4108 km of field deployed submarine cable.

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1. Introduction

The popularity of new high-bandwidth data services such as high-definition video and cloud storage has fueled a tremendous need for capacity growth across the entire telecommunication infrastructure. In recent years this has driven an industry-wide effort to develop the components, subsystems and systems required to upgrade networks to 100G line rates. From this, coherent-detected polarization-multiplexed, quadrature phase shift keying (CP-QPSK) has emerged as the industry-wide standard for 100G transport. CP-QPSK modulation is based on coherent detection technology and digital signal processing, which offer many advantages including the compatibility with a 50-GHz channel grid, dispersion un-managed transmission and electronic polarization-mode dispersion compensation.

100G coherent transponder technology can be deployed both by upgrading existing 10G-optimized transmission systems, as well as through the Greenfield deployment of 100G-optimized overlay networks. An overlay network allows for the optimum transmission performance and therefore the most scalable and cost-effective approach towards large-scale 100G deployment, making this the preferred approach for most terrestrial networks. This avoids the additional complexity and transmission impairments that can occur when legacy networks with installed 10G channels are upgraded with coherent technology.

The capacity upgrade of submarine cable networks is significantly more challenging when compared to terrestrial networks. Greenfield deployment of a new submarine cable network is tremendously expensive and requires a long lead time for planning, certification and deployment. This has resulted in a surge of submarine line terminal equipment (SLTE) upgrades [1-2] where legacy 10G line terminals are replaced with 40G transponder technology. More recently, experiments using re-circulating loop configurations have shown that with state-of-the-art amplifier and fiber technology it is feasible to transmit 100G line rates over the transmission distances of interest to submarine networks [3-5]. However, to the best of our knowledge, no 100G field trials on deployed submarine cables have been reported so far.

In this paper we discuss the results of a field trial on a submarine cable system deployed between Florida and Puerto Rico. We successfully transmitted 125-Gbit/s CP-QPSK modulated signal over 2054 km (uni-directional) and 4108 km (bi-directional) of field deployed submarine cable. This demonstrates the feasibility of a ten-fold capacity upgrade in comparison to the original design capacity of the cable system.
2. Submarine cable and terminal configuration

The field trial has been carried out on a deployed submarine cable network between Boca Raton, Florida, and San Juan, Puerto Rico, as shown in Fig. 1 [6]. The segment consists of 36 spans and has a typical span length of 57 km, with a total uni-directional transmission distance of 2054 km. The dispersion map is based on hybrid spans with a combination of large mode field (LMF) fiber with an effective area of >72 \( \mu m^2 \) and dispersion coefficient of -3.9 ps/nm/km (at 1550 nm), respectively, and high dispersion fiber (HDF) with an effective area of 50 \( \mu m^2 \) and dispersion coefficient of -2.7 ps/nm/km, respectively. Periodic dispersion compensation is achieved with non-dispersion shifted fiber (NDSF) with an effective area of >75 \( \mu m^2 \) and a dispersion coefficient of +20 ps/nm/km. The effective zero dispersion wavelength of the complete segment is at 1550 nm.

The inline amplifiers operate at a fixed operating point that minimizes spectral tilt along the cable segment, which requires a constant total output power. Since only a few channels have been transmitted in the field trial, loading channels are used for stabilization of the cable segment. The loading channel generator (LCG) consisted of five tunable quasi-CW channels, optimized such that they do not incur any transmission impairments when co-propagating at high power close to the CP-QPSK transmission channels. The LCG channels are set such that the total amplifier output power is kept constant, independent of the actual channel power of the transmission channels. This allows us to vary the channel power of the CP-QPSK channels during the field trial in order to optimize transmission performance, while not changing the working point of the in-line amplifiers. The LCG channels are added to the CP-QPSK transmission channels after the multiplexer structure (Fig. 1) and the optical power of all channels combined is used to monitor the total power launched into the wet plant.

The optimum per-channel pre-compensation is as well a crucial parameter to optimize transmission performance over the submarine cable segment. The simulation results depicted in Fig. 2 depict the optimum pre-compensation as a function of wavelength on a comparable submarine segment, which shows the importance of a matched pre-compensation. In the field trial the pre-compensation is optimized using a tunable dispersion compensator (TDCM). However, the optimum per-channel pre-compensation is fully deterministic and in actual system deployment slope-adjusted fiber Bragg gratings (FBGs) can be used instead of TDCMs.

Fig. 2: (a) Optimum pre-compensation as a function of wavelength, simulated for a different cable segment with comparable design (b) Delta power between 40G and 100G CP-QPSK, (c) Received optical spectra after 4108 km transmission.

The transmitted 125-Gb/s CP-QPSK signal has been generated by a prototype unit. A CW light source is first pulse-carved with 50% duty-cycle to generate return-to-zero signals. The signal is then split, and each of the tributaries is QPSK modulated with a \( 2^{15} \)-1 PRBS at a 31.25-Gbaud line rate (at total of 100G payload plus 4% protocol overhead and 20% FEC overhead). The two signals are subsequently combined by means of a polarization beam combiner (PBC). At the receiver, the signal is mixed with a local oscillator in two 90° optical hybrids. The in-phase and quadrature components of both polarizations are then converted to the electrical domain using 4 single-ended photo diodes and subsequently analog-to-digital sampled at a 50-Gsample/s sampling rate by a Tektronix (DSA72004B) digital storage scope. A total of 2·10^6 samples are used for off-line signal processing [3].

The transmitted / received signal is (de-)coupled from the installed terminal equipment by means of a 3-dB coupler. A 125-Gb/s CP-QPSK center channel with 4 x 43-Gb/s CP-QPSK neighbor channels is transmitted in order to emulate a WDM transmission on a 50-GHz channel grid (Fig. 2c). The nonlinear transmission penalty resulting from co-propagating 43-Gb/s CP-QPSK neighbors is significantly higher compared to 125-Gb/s CP-QPSK channels, as shown by simulations in Fig. 2b. This is a result of the lower symbol rate, which enhances the cross phase modulation impairments. The channel power of the co-propagating 43-Gb/s CP-QPSK neighbors has therefore been reduced by 1.5 dB relative to the 125-Gb/s CP-QPSK center channel, such that the nonlinear tolerance of 125-Gb/s CP-QPSK channels on a 50-GHz channel grid is correctly emulated.
Field trial results

The 125-Gb/s CP-QPSK transmission performance is first characterized in a uni-directional configuration with a transmission distance of 2054 km, transmitting the signals from San Juan to Boca Raton. Fig. 3 shows the obtained transmission results for single channel transmission (together with the LCG channels) as well as the transmission performance with the 43-Gb/s CP-QPSK neighbors on a 100- and 50 GHz grid. The channel under test is placed close to the middle of the available spectral band, at 1552.12 nm.

In each of the measurements, both the optimum channel input power as well as the optimum pre-compensation is determined. Fig. 3a shows that the optimum channel input power into the fiber for a single channel transmission is approximately -5 dBm, and does not change significantly with neighbors placed on a 100 GHz grid. A slight decrease of the optimum launch power to -6 dBm per channel is measured when the co-propagating channels are placed on a 50-GHz spaced WDM grid. Fig. 3b shows the pre-compensation sweep with the co-propagating channels on a 100-GHz grid. The optimum pre-compensation is -300 ps/nm, which is in-line with the simulations results shown in Fig 2a that predict a close to 0 ps/nm optimum pre-compensation near the middle of the transmission band. The measured margin with respect to a $1.4 \cdot 10^{-2}$ (6.8 dBQ) FEC threshold is approximately 3 dBQ at the optimum power. Note that the 125-Gb/s CP-QPSK channel is located close to the zero-dispersion wavelength where, due to the lower signal walk-off, we expect the worst transmission performance across the transmission band.

In the second step, the signal is optically looped back in Boca Raton, resulting in a bi-directional 4108 km transmission link, and both transmitter and receiver are now located in San Juan. The optimum channel power and pre-compensation are shown in Fig 4a and Fig. 4b, respectively. This shows an optimum channel input power of -7 dBm when the co-propagating channels are placed on a 50-GHz spaced grid. The optimum pre-compensation is now -500 ps/nm, which is as expected approximately double the optimum of the uni-directional configuration. The measured margin with respect to the FEC threshold is approx. 0.7 dBQ at the optimum power and pre-compensation, which shows that 125-Gb/s CP-QPSK transmission is feasible over the 4108-km of submarine cable.

5. Conclusion

In this paper we show, to the best of our knowledge, for the first time the transmission of 125-Gb/s CP-QPSK over >4000 km of field deployed submarine cable. Measurements after a 2054-km and 4108-km transmission distance show performance above the FEC threshold, demonstrating the suitability of 125-Gbit/s CP-QPSK for deployment on legacy submarine infrastructure. This confirms that existing submarine links can be upgraded to 100G line rates, thereby significantly extending their design capacity and delaying the need for new cable deployments.

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References