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100G Transoceanic Length Transmission with High Spectral Efficiency Using Bandwidth Constrained PDM-QPSK

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Abstract: We review our recent 100G, high spectral efficiency, transmission experiments over transoceanic and regional distances. Transmitter pre-filtering together with a MAP detection algorithm can significantly improve spectral efficiency.

OCIS codes: (060.2330) fiber optics communications; (060.1660) coherent communications

1. Introduction

Global IP traffic is projected to grow at a compound annual rate of 34% driven by Internet video (especially high definition video) and P2P (peer-to-peer file sharing) [1]. To satisfy the insatiable demand for capacity, transmission technologies that support higher data rate and higher spectral efficiency (SE) are needed. However, the transport of high data rate WDM channels at high SE over transoceanic distances requires innovative solutions to numerous technical challenges. Advanced modulation formats and detection schemes provide solutions to many of the challenges. Various modulation formats requiring low bandwidth to maximize SE or limiting the deleterious effects of fiber nonlinearities have been investigated including multi-level quadrature amplitude modulation (QAM), polarization division multiplexing (PDM), orthogonal frequency division multiplexing (OFDM), etc. Higher-order QAM formats offer extremely high SE, but so far their system reach is limited to less than transoceanic distances. Therefore, most transoceanic distance transmission demonstrations with >200% SE were based on the PDM-QPSK modulation format. Figure 1 summarizes transmission distance vs. SE from recent published results for distances over 4,000 km [3-8]. Three contour lines of distance–SE products (10, 20, and 30 Mm-bits/s/Hz) are also plotted for easy reading. In the past 1½ years, the digital coherent technology has pushed 100G transmission from ~7,000 km [3] with 200% SE up to 10,000 km with 360% SE [8].

In this paper, we review our recent 100G transoceanic length transmission experiments with ≥300% SE. With transmitter pre-filtering and a multi-symbol maximum a posteriori probability (MAP) detection algorithm, 14,000 km with 300% SE, 10,000 km with 360% SE, and 5,000 km with 400% have been demonstrated.

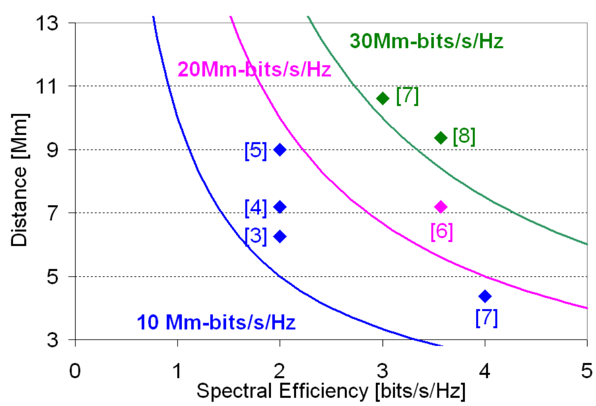

Fig. 1: Published transmission distance vs. spectral efficiency results from Refs. [3-8].

2. Pre-filtered PDM-QPSK modulation format and MAP detection algorithm

One simple but effective way to increase SE is to reduce the signal bandwidth (BW) by pre-filtering. Pre-filtering can effectively limit crosstalk from neighboring channels; however, aggressive pre-filtering also dramatically increases inter symbol interference (ISI) causing significant performance penalty for single symbol detection techniques. On the other hand, the pre-filtering induced ISI can also be interpreted as memory which can be exploited by advanced multi-symbol detection algorithms such as MAP [9] or MLSE [10] to mitigate the performance penalty normally associated with ISI [7-11].

3. 96ch x 100 Gb/s transmission over 10,600 km with 300% SE

In our 96chx100 Gb/s experiment, WDM channels with 33.3 GHz spacing were transmitted over 10,600 km on a state-of-the-art test bed. The details of the transmitter, receiver, test bed, and coherent detection algorithms can be found in [7]. Figure 2 shows the Q-factor and MAP benefit vs. transmitter pre-emphasis. Approximately 1.8 dB performance improvement was achieved by employing MAP detection. Figure 3 summarizes the measured performance of all 96 channels; all channels performed better than 10.2 dB, which translates to ~2-dB FEC margin relative to a continuously interleaved BCH code [12].

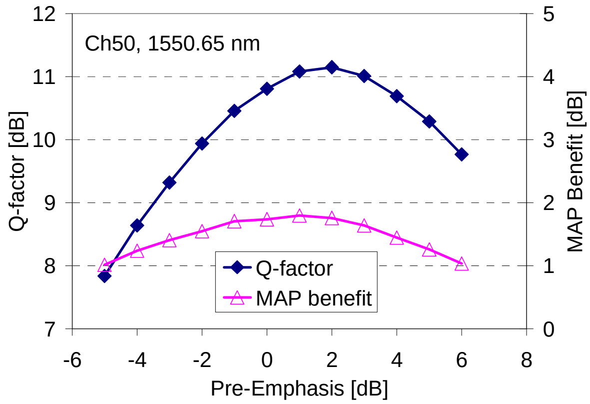

Fig. 2: Q-factor and MAP benefit vs. transmitter pre-emphasis after 10,600 km (300% SE).

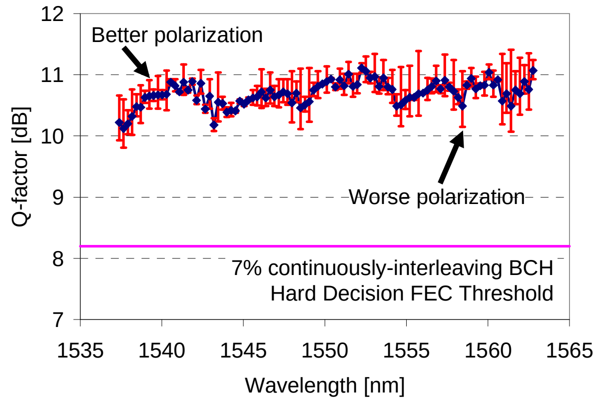

Fig. 3: Q-factor after 10,600 km (300% SE)

4. 112ch x 100 Gb/s transmission over 9,360 km with 360% SE

Many technologies have been proposed and studied for operating channels at a channel spacing equal to the baud rate (Nyquist spacing) including: coherent WDM [13], coherent OFDM with orthogonal multiplexing [6], coherent OFDM with non-orthogonal multiplexing [14], and Nyquist WDM [15, 16]. In particular, ref [6] and [16] demonstrated transoceanic distance transmission with Nyquist channel spacing.

MAP detection algorithm can also be applied in systems with Nyquist channel spacing [8]. Figure 4 shows the Q-factor and MAP benefit vs. transmitter pre-emphasis after 9,360 km transmission distance on our test bed. Approximately 3.5 dB performance improvement was achieved with MAP detection. Figure 5 summarizes the performance of all 112 channels; all channels performed better than 10.2dB, translating to ~2-dB FEC margin relative to the FEC threshold in [12].

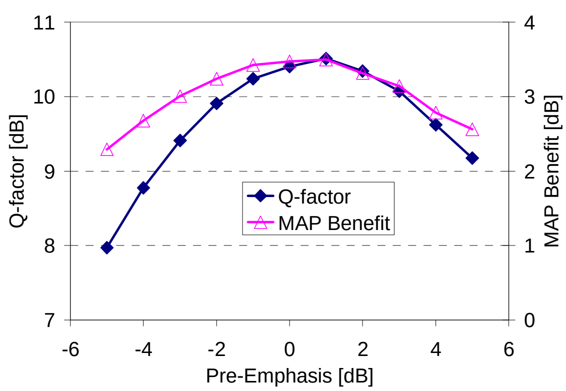

Fig. 4: Q-factor and MAP benefit vs. transmitter pre-emphasis after 9,360 km (360% SE).

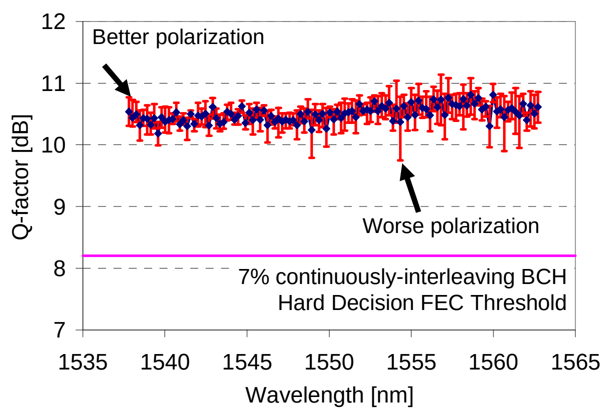

Fig. 5: Q-factor after 9,360 km (360% SE).

5. 128ch x 100 Gb/s transmission over 4,360 km with 400% SE

We achieved 400% SE with the PDM-QPSK format by pre-filtering using optical interleaving filters (OIF). With single symbol detection the pre-filtering caused significant penalty as shown by the solid-circle curve in Figure 6. However, our MAP detection algorithm recovered up to 6 dB Q-factor (open triangles) and the performance reached ~12 dB for 25 GHz spaced 28 GBaud signals (solid-diamonds). Figure 7 shows the performance of 12 select channels across the transmission band after 4,360 km transmission distance. The average of the 12 channels was 10.2 dB, ~2 dB above the FEC threshold in [12]. More detailed results on the 400% SE experiment can be found in [20] and [21].

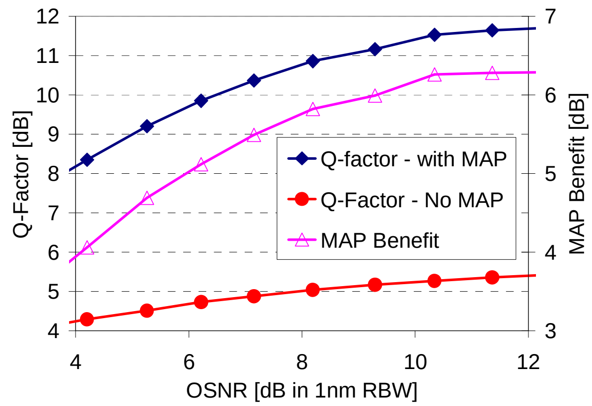

Fig. 6: Back to back performance and MAP benefit vs OSNR for 400% SE

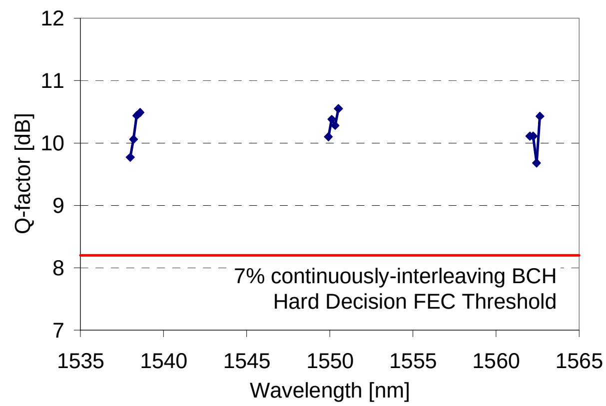

Fig. 7: Q factor after 4,360 km (400% SE).

6. Discussion

The results reported so far are limited by the available optical power in our test bed amplifiers. To explore the maximum achievable distance for each SE, we also performed Q-factor vs. transmission distance measurements at the optimum channel power for each distance. Based on a 10 dB Q-factor target, the achievable distances are 14,000 km for 300% SE, 10,000 km for 360% SE, and 5,000 km for 400% SE.

As shown in the preceding sections, the MAP benefit depends on the operating OSNR, the pre-filtering BW (i.e. the channel spacing), linear crosstalk from neighboring channels, and the number of taps used in the MAP implementation. The lower the received OSNR, the smaller the MAP benefit as the noise induced penalty starts to dominate the overall penalty (see Figs. 2, 4, and 6). The narrower the pre-filtering BW (i.e. the stronger the ISI and the smaller the crosstalk from neighboring channels) the larger the MAP benefit. MAP benefit increases from 1.8 dB to 6.5 dB when the channel spacing is reduced from 33.3 GHz to 25 GHz for 28 GBaud PDM-QPSK signals. Also, the higher the number of taps in the MAP algorithm, the higher the MAP benefit. However, more taps require more computations. 5-tap MAP was used for all the results shown in this paper.

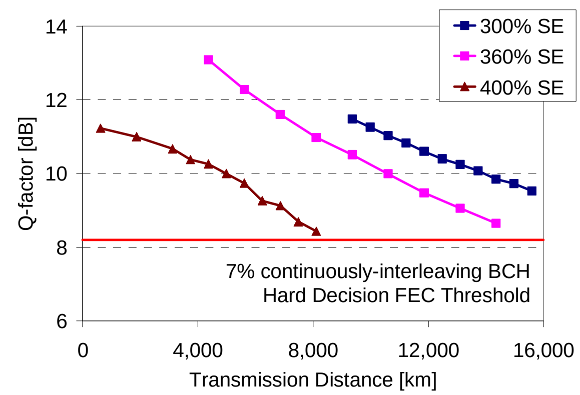

Fig. 8: Q factor vs transmission distance for 300%, 360% and 400% SE

7. Conclusions

Pre-filtered PDM-QPSK is a simple and effective way to increase SE. Aggressive filtering removes crosstalk from neighboring channels and induces correlation between symbols. A MAP based multi-symbol detection technique can mitigate the pre-filtering induced ISI penalty by taking advantage of the memory induced by the pre-filtering. With the aid of the MAP detection algorithm, we have extended the 100G transmission distance for 300%, 360% and 400% SE to 14,000 km, 10,000 km, and 5,000 km, respectively, with Q-factors >10 dB.

8. References

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