Experimental Demonstration of Coherent MAP Detection for Nonlinearity Mitigation in Long-Haul Transmissions

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Abstract: We implemented a maximum a posteriori probability (MAP) detection scheme for mitigating nonlinear phase distortion. We demonstrated 1 dB improvement in system performance and ~2dB higher nonlinearity tolerance after 6,000 km transmission.

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1. Introduction

The most cost effective way to enhance transmission capabilities of long-haul WDM systems is to improve the performance of terminal equipment. The expected increase in future capacity demand could be satisfied with spectrally efficient modulation formats in concert with coherent detection and higher data rates. However, it has been shown that nonlinear phase distortion may significantly degrade coherent-detection performance and diminish the advertized receiver-sensitivity advantage over a noncoherent detection scheme [1, 2]. Nonlinear transmission effects will be a major limiting factor as high bit rate and spectrally efficient systems require higher signal power to ensure adequate signal to noise ratio at the receiver. Thus the need for nonlinearity mitigation is an important priority in transmission research. The past few years have witnessed significant improvement in nonlinear tolerance with the introduction of more linear transmission fibers, better modulation formats, and stronger error correction codes. Coherent detection offers another opportunity to mitigate nonlinearity using digital signal processing (DSP).

One method proposed in [3, 4] mitigates the nonlinear phase distortion based on estimating phase distortion as a function of received signal intensity. Other methods described in [5, 6] compensates nonlinear distortion with digital back-propagation. The effectiveness of the intensity-based estimation method is limited when optical signal intensity changes significantly due to chromatic dispersion. The back-propagation method requires extensive amount of calculations and faces a challenge in implementation complexity. In this work we propose and investigate a maximum a posteriori probability (MAP) detection scheme for nonlinearity mitigation in long-haul transmission experiments using coherent detection. Our MAP algorithm is based on the fact that intra channel nonlinear effects show strong data-pattern dependency. Experiments were conducted on a broadband WDM test bed utilizing EDFA coupled to 100 km spans with large effective area fibers. We achieved transoceanic transmission with a coherent receiver employing MAP detection for 40 Gb/s return-to-zero (RZ) quaternary phase-shift-keying (QPSK) signals on 33 GHz channel spacing with a spectral efficiency of 1.2 bit/s/Hz. We obtained more than 1 dB improvement in peak performance and about 2 dB improvement in nonlinear tolerance to channel power.

2. MAP Detection for Data-Pattern Dependent Nonlinearity Mitigation

Impairments induced by fiber nonlinear effects such as self phase modulation can be highly data-pattern dependent. Figure 1 shows phase distortions of received symbols resulting from a single-channel nonlinear 5,000 km propagation simulation. We used a 7-symbol window sliding through the received sequence and the phase distortions of the center symbol in the window are shown in groups based on the data patterns in the window. Each labeled group includes up to 4 inverted/flipped data patterns depending on pattern symmetry. For instance, the 0000001 group includes 4 patterns, i.e., 0000001, 1111110, 1000000, and 0111111, whereas the 0111110 group has only 2 patterns, i.e., 0111110 and 1000001. We can see that the phase distortions in the same group have similar values but can be quite different from other groups. This shows the strong pattern dependency of the intra channel nonlinear impairments.

Based on this data-pattern dependency observation, we used an *N*-tap MAP scheme for nonlinearity mitigation. Figure 2 depicts a structure diagram of the nonlinearity mitigating system. A coherent receiver is employed to detect the electrical field of the received signal. At the initial stage of system operation, a preset training sequence (such as a PRBS) can be transmitted through the transmission line and the received signal samples are fed into a training processor. The training processor arranges the received signal samples into data-pattern dependent sets based on the data in an *N*-symbol window around each symbol. Then, all *N*-symbol samples in each set are averaged to reduce noise or other random impairments. The averaged signal samples of all the pattern sets are stored in a memory as a table indexed by the data pattern. An example table of distorted 5-bit signals is shown in Table 1. During normal system operation, the table of distorted signal can be updated by utilizing preset non-user data, which makes the penalty mitigation adaptive to slow changes in the transmission systems.

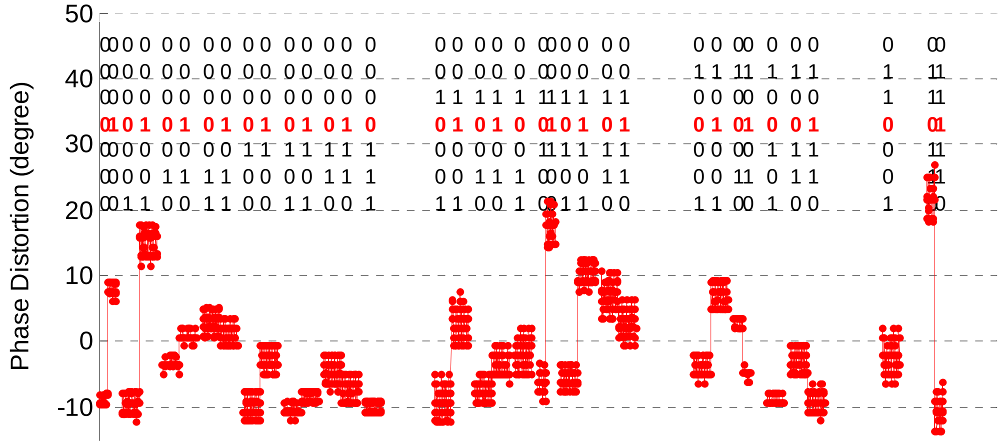


Figure 1: Phase distortion samples of center symbols in a 7-symbol sliding window shown in symmetric pattern groups (e.g. 0000001 group = {0000001, 1111110, 1000000, 0111111}, and 0111110 group = {0111110, 1000001})

Received user data samples in an *N*-symbol shifting window are fed into a MAP detector. The a posteriori probability is calculated based on the Euclidean distance or correlation between the received signal and entries in the table of distorted signal. The pattern in the table that has the shortest Euclidean distance or highest correlation to the received signal is chosen as the MAP decision.

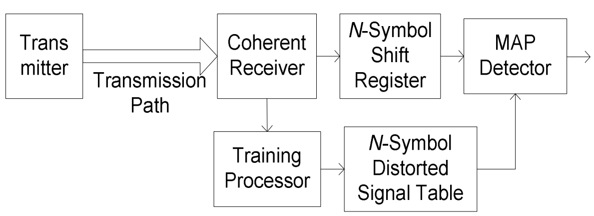


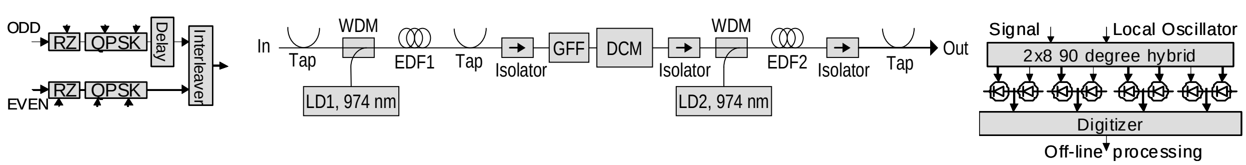
Figure 2: MAP detection system for nonlinearity mitigation

Table 1: Example table of averaged 5-bit distorted signal

Bit Pattern	Averaged Samples of Distorted Signals
00000	0.3-0.1i 0.3-0.2i 0.3-0.1i 0.3-0.1i 0.4-0.1i
00001	0.3-0.0i 0.3-0.0i 0.4+0.0i 0.4-0.0i -0.4+0.1i
……	……
11111	-0.4-0.2i -0.4-0.1i -0.3-0.1i -0.4-0.0i -0.4-0.1i

3. Experiments

Figure 3 shows the schematic of the 40G coherent RZ-QPSK experiments. Single polarization RZ-QPSK signals are generated using an I&Q data modulator and an MZ intensity modulator. The two paths are modulated with 2^{23}-1 data and inverted data patterns at a symbol rate of 23 GS/s. The digital coherent receiver is based on data acquisition with a real time oscilloscope and subsequent off-line post processing. A slope matched 28 nm test bed was employed with dual-stage EDFAs coupled to 100 km spans with large effective area fibers (~130 μm^2). The nominal launch-power into the transmission spans was approximately 21 dBm. The dispersion map had a period of 600 km with a dispersion accumulation of 2000 ps/nm before compensation. The transmission band was loaded with DFB lasers, and the measurement region was replaced with eight ECL lasers each with a linewidth of 360 kHz. We used 33 GHz channel spacing thus achieving a spectral efficiency of 1.2 bit/s/Hz.



a. Transmitter b. Dual-stage EDFA with mid-stage dispersion compensating module c. Receiver

Figure 3: Schematic of RZ-QPSK transmitter, dual-stage EDFA, and coherent receiver in transmission experiments

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In the offline DSP, we processed 4M-bit data for each measurement point. The MAP detector was trained and a signal distortion table was generated by using the first 1M bits. The signal distortion table was then applied to all the 4M bits in MAP detection. All 4M bits were counted in calculating a Q factor with the observation that the MAP detection on the first 1M bits showed no advantage over the remaining 3M bits.

Experiments were performed to compare different detection schemes including, noncoherent differential QPSK (DQPSK), coherent DQPSK, and coherent differential coding QPSK (DCQPSK) [7] with and without MAP detection. The noncoherent DQPSK is measured with a differential interferometer and direct detection receiver. The coherent DQPSK and DCQPSK transmitters were similar and both had the data differentially precoded prior to the phase modulator. The coherent DQPSK receiver coherently demodulates the signal and detects absolute phases, but it makes decisions on differential phases of consecutive symbols without carrier phase recovery. The coherent DCQPSK receiver on the other hand required carrier phase recovery and differential decoding.

Figures 4 shows the pre-emphasis curves covering linear, quasi-linear, and nonlinear regimes at 18 dBm EDFA output power after 4,200 km transmission. We observed that the difference in Q-factor between the conventional coherent DCQPSK curve (i.e., without MAP) and the noncoherent DQPSK curve degrades at high signal power. On the other hand, the coherent DQPSK showed similar nonlinear tolerance as the noncoherent DQPSK, which agrees well with previous simulation results [1]. By employing a 5-tap MAP detection, however, the performance and nonlinearity tolerance of the coherent DCQPSK was significantly improved. After 4,200 km transmission, the optimum Q-factor and nonlinearity tolerance were increased, by about 0.7 dB and 2 dB, respectively. The small improvement with MAP detection in the linear region of the pre-emphasis curve was attributed to the inter symbol interference induced by limited receiver bandwidth.

Figure 5 compares the performance of a channel at 1550.1 nm as a function of distance employing different detection schemes. We observed Q-factor improvement with coherent detection degrades as distance increases and system becomes more nonlinear. Without the MAP detection, the coherent DCQPSK format performed worse than the noncoherent DQPSK after 6,000 km transmission, which indicates severe nonlinear impairments. The 5-tap MAP detection, however, boosted the Q factor by about 1 dB. The 7-tap MAP detection further improved the Q factor by another 0.3 dB, at which point we note that the improvement became insignificant with the addition of more taps in MAP detection. The results (Fig. 4 and 5) show that the proposed MAP detection scheme can effectively mitigate the penalty induced by data-pattern dependent nonlinear effects.

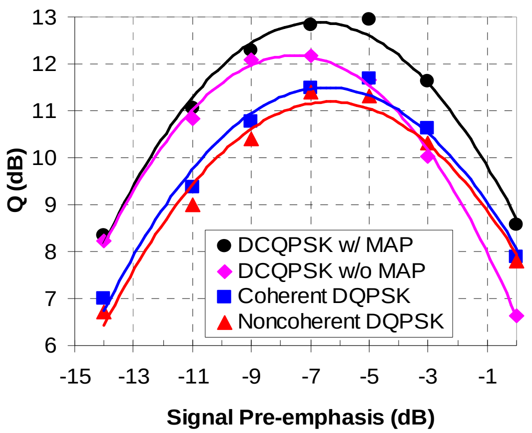

Figure 4: Performance comparison with pre-emphasis sweep

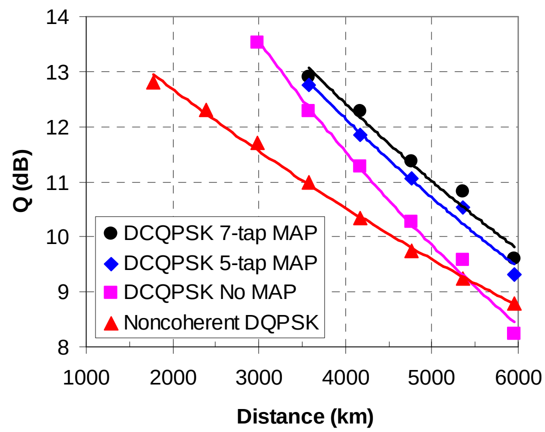

Figure 5: Performance comparison at different distance

4. Conclusions

We experimentally investigated a MAP detection scheme for nonlinearity mitigation in long-haul transmission. Transoceanic transmission of 40 Gb/s RZ-QPSK signals with 1.2 bit/s/Hz was achieved with a coherent receiver employing MAP detection. More than 1 dB improvement in peak performance and about 2 dB improvement in nonlinear tolerance to channel power were demonstrated with the proposed MAP-detection scheme designed to mitigate data-pattern dependent nonlinear impairments.

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