Training-Aided PDM 64-QAM Transmission with Enhanced Fiber Nonlinearity Tolerance

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Abstract: We show that fiber nonlinearity compensation of just the training sequence improves the nonlinearity-limited performance of training-aided m-QAM systems. Experimental results demonstrate transmission performance improvement by 0.4 dB for a 120-Gb/s 64-QAM 800-km system.

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1. Introduction

Polarization-division-multiplexing (PDM) and high-order quadrature amplitude modulation (QAM) formats in combination with coherent detection provide high spectral efficiency (SE) [1]. Recently, considerable research has been conducted on single-carrier PDM 64-QAM systems [2-5]. In all of previous demonstrations, the digital signal processing (DSP) design includes multi-stage multiple-input multiple-output (MIMO) blind adaptive polarization de-multiplexing (pol-demux) and phase recovery. 64-QAM requires longer convergence time and higher computational resources than lower QAM format systems such as QPSK. In contrast, training-aided channel estimation (TA-CE) [6-9] is a format-transparent pol-demux solution and is not subject to decision ambiguity, which becomes a significant problem in high-order QAM systems. TA-CE offers more benefits when applied to higher-order QAM systems. However, a 64-QAM system using TA-CE has yet to be demonstrated experimentally. Furthermore, the performance of TA-CE has not been investigated in the presence of fiber nonlinearity.

In this paper we first compare the performance of TA-CE and blind adaptive schemes with nonlinear transmission. We show that TA-CE provides superior amplified spontaneous emission (ASE) limited performance as blind equalization, but has a poorer fiber-nonlinearity-limited performance. We then propose and demonstrate that digital backpropagation (DBP) [10] of *just* the TS (which is computationally inexpensive) improves the nonlinearity-limited performance of TA-CE beyond that of blind equalization. The benefit of our nonlinearity tolerant (NLT) TA-CE system is verified using both numerical simulations and experimental measurements for a 120-Gb/s 10-Gbaud 64-QAM 800-km system. We find that NLT-TA-CE improves the received signal Q^2 by 0.4 dB at optimal launch power and by up to 1.6 dB in the highly-nonlinear region compared with conventional TA-CE.

2. Nonlinear-tolerant training-aided channel estimation

For a coherent optical system with linear equalization only, the performance penalty at higher powers is due to two factors: (*i*) signal is distorted by fiber nonlinearity, (*ii*) nonlinearity degrades the linear CE. Although (*i*) is the dominant factor and could be mitigated using nonlinearity compensation [10, 11], high computational complexity prevents real-time implementation. Therefore, it is prudent to consider optimizing factor (*ii*) independently.

With blind adaptive pol-demux, the linear CE performance depends on the data used for convergence; therefore, blind equalization works well when the nonlinearity impairment of the information signal is removed. With conventional TA-CE, the ASE noise is usually mitigated using boxcar averaging over several received TSs; however, nonlinear noise cannot be averaged out since it is data-pattern dependent. Since all TS blocks are identical, so is the nonlinear distortion. If we can mitigate the nonlinear errors of the training sequence only, using DBP, we should be able to achieve a substantial improvement with minimal computational effort.

The proposed NLT-TA-CE structure is illustrated in Fig. 1(a). The received TS (R_{TS}) first passes through a DBP module (TS-DBP) for nonlinearity compensation, and then TA-CE is used to estimate the 2×2 MIMO PDM channel **H** [7]. Assuming no nonlinear compensation for data signals, the NLT-TA-CE is obtained after combining **H** with the CD transfer function (i.e. multiplying the CD transfer function with each of the four components of the 2×2 channel matrix linearly). Finally, the equalizer coefficients are setup according to MMSE criterion.

The optimality of linear equalizers was examined with a 20-Gbaud single-channel PDM simulation over 800-km transmission. VPItransmissionMaker 8.7 was used for simulation with all standard linear and non-linear channel parameters based on split-step Fourier method fiber model (key parameters: 100-kHz laser linewidth, ±1 GHz frequency offset, nonlinear coefficient of 2.6×10^{-20} m^2/W, PMD coefficient of 5-ps/km$^{1/2}$ and 6-dB EDFA noise figure). QPSK was used as the modulation format for the sake of simplicity of adaptive algorithms. The training sequence based channel estimation is as in [7] and standard CD equalization combined with a constant modulus algorithm (CMA) [12] was used for blind equalization.

Figure 1(b) shows the *Q*-factor (derived from constellation variance) with linear equalization only. It is clear that TA-CE is slightly better than blind adaptive equalization in the linear region (from -6 to 0 dBm). The blind equalizer achieves better linear channel acquisition than TA-CE when the launch power is beyond the nonlinear threshold. This is because the inaccuracy of the linear CE of TA-CE, caused by the fiber nonlinearity distorting the TS, is more severe than the increased convergence error of adaptive algorithm due to fiber nonlinearity. The NLT-TA-CE with 1 step-per-span (sps) TS-DBP offers about 0.5-dB Q-improvement at the optimal launch power compared with the normal TA-CE, making the performance similar to the blind adaptive scheme within the highly nonlinear region. It is worth mentioning that the performance in the linear region becomes slightly enhanced (0.1 to 0.2 dB) because the linear CE is also improved even in the weak nonlinear region. Increasing the number of steps to 4 sps for TS-DBP can only improve performance slightly, since the system performance is still limited by the nonlinear distortion of the information symbols. Thus, we used 1 sps TS-DBP for the rest of the paper to minimize the computational complexity. Since the TS is only a small proportion of the total signals (e.g. 1.96% in [7]) so the additional TS-DBP process adds only a negligible computational burden to the total system.

In order to show the difference between these two linear channel equalizers more clearly, DBP with 1 sps [10] was applied to the information symbols before pol-demux. As shown in Fig. 1(c), adaptive channel acquisition is also improved by using the information data with DBP. Therefore, the blind equalizer outperforms conventional TA-CE (where CD is removed from TA-CE) in the nonlinear regions with about 1.5-dB higher peak *Q*-performance. This difference is purely due to the difference between the optimal and the nonlinearity distorted linear channel estimations, confirming the validity of factor (*ii*) in the previous discussion. When applying NLT-TA-CE to the data symbols with DBP, the performance catches up with the blind adaptive scheme. Simulation results verified that by optimizing the linear CE using NLT-TA-CE, the nonlinear transmission performance with linear equalization can be enhanced. Also, the NLT-TA-CE can only be implemented with the TS, which are able to cover the whole channel memory (mainly CD memory). It is not applicable for systems with CD equalization and short TS for pol-demux only [8, 9]. Furthermore, the performance of NLT-TA-CE may be improved by using advanced DBP techniques such as low-pass filtering (LPF) assisted DBP [11].

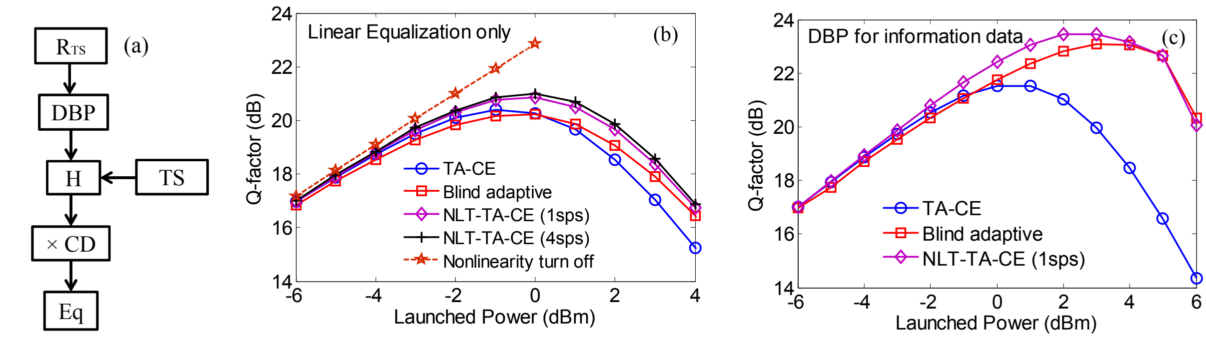

Fig. 1. (a) Structure for NLT-TA-CE, and simulation results with: (b) linear equalization only and (c) 1sps DBP applied to information symbols.

3. PDM-64QAM experimental demonstration and discussion

Figure 2(a) shows the block diagram of the experimental setup. A 10-Gsamples/s arbitrary waveform generator (AWG) generated baseband signals that drive an optical I/Q modulator. The output of the transmitter laser was then modulated to provide the optical signals. PDM was emulated by splitting the optical signals into two paths with a polarization beam splitter (PBS), where one path experienced 19600-ps delay relative to the other. The two tributaries were recombined through a polarization beam combiner (PBC). The transmitted PDM signal structure is shown in Fig. 2(b). To implement a Golay sequence pair with Alamouti coding as the TS [7], we sent four sequence blocks in X-polarization before information data; each block contained two guard intervals (17 symbols each) and TS (64 symbols) to allow two blocks' length to match exactly the polarization delay. Blocks A and C are Golay pairs; the spectra of blocks B and D were set to –conj(FFT(C)) and conj(FFT(A)), respectively. As shown in the constellation diagram in Fig. 2(b), the information bits were modulated with 64-QAM format, while the TS used QPSK with scaling to the four highest amplitude points of 64-QAM (red points) to achieve the best training to noise ratio. The training block was repeated after every 10000 information symbols for polarization tracking. After accounting for a 20% FEC overhead, the net spectral efficiency is 9.804 b/s/Hz. After transmitting through 800 km with an EDFA every 80 km, the received signals were first filtered by a waveshaper (WS), used as an optical bandpass filter, and then fed into an optical hybrid followed by 18-GHz balanced receivers. The transmit laser and local oscillator are both external cavity lasers with 100-kHz linewidths, and the LO was tuned to within 100 MHz of the transmitter. The signals were captured by a 40-Gsamples/s real-time digital oscilloscope for offline processing.

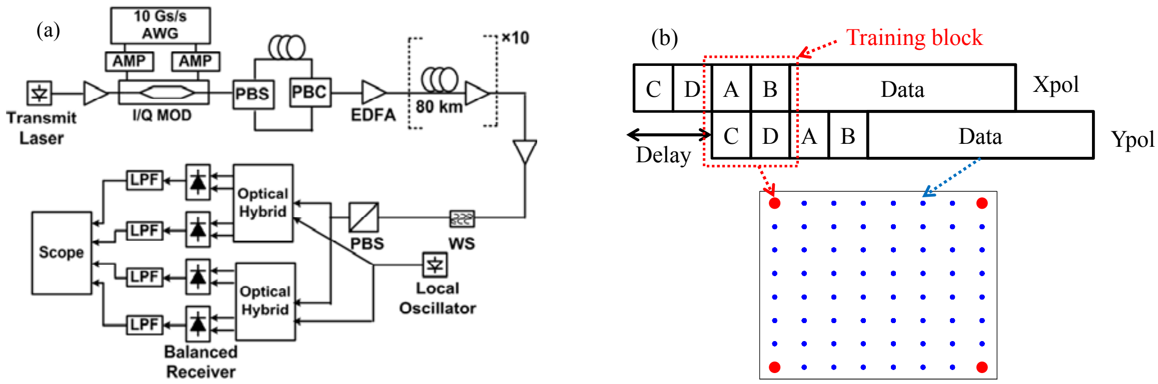

Fig. 2. (a) Experimental setup, (b) transmitted signal structure. AMP: RF amplifier, I/Q MOD: I/Q modulator.

For the receiver's DSP, after frequency offset compensation and frame synchronization, the TS were extracted for CE. A low-complexity polyphase 2×2 MIMO frequency-domain equalizer was then used to remove all of the linear impairments. After decision-aided maximum likelihood phase estimation [13], the Q^2-factor was calculated using $Q^2(dB) = 20\log_{10}(\sqrt{2}erfc^{-1}(2BER))$. Figures 3(a) and (b) show the measured results for TA-CE and NLT-TA-CE systems with different launch powers for 480-km and 800-km transmission, respectively. The NLT-TA-CE improves performance at higher launch powers, resulting in a 0.4-dB Q^2-factor increase resulted from using NLT-TA-CE after 800-km transmission at the optimal launch power of -3 dBm. The performance is improved by 1.6 dB at 1 dBm launch power.

Q^2 versus transmission distance is shown in Fig. 3(c), where the results are taken at the optimal launch power for each distance. The performance enhancement due to NLT-TA-CE increased with distance. The system can achieve error-free transmission after 800 km assuming 20% soft decision forward error correction (SD-FEC) with a 5.7-dB Q^2 requirement [14]. The equalized constellation diagrams of X and Y polarization signals with NLT-TA-CE at -3 dBm launch power are also shown as the insets of Figs. 3(a) and (b). The inset of Fig. 3(c) shows the equalized signals at back to back transmission.

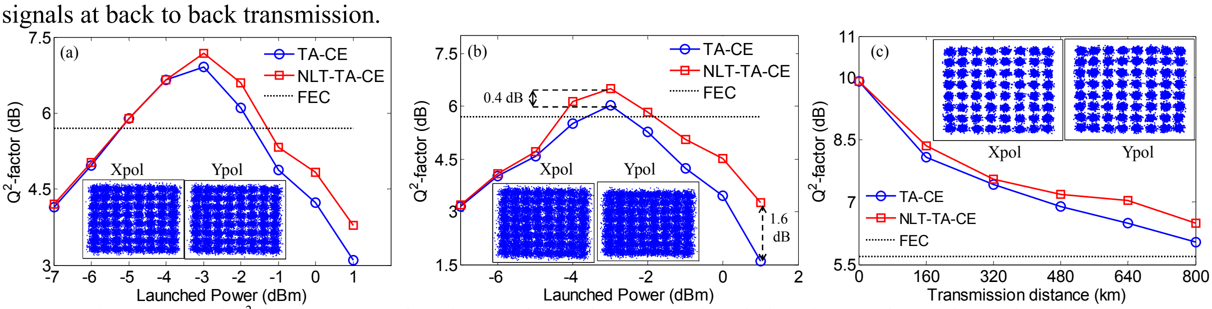

Fig. 3. Measured Q^2-factor versus: (a) launch power for 480-km transmission, (b) launch power for 800-km, and (c) distances.

4. Conclusions

We report single-carrier PDM-64QAM transmission with nonlinearity tolerant TA-CE scheme. Based on removing the nonlinearity of the received TS using DBP, the proposed method is able to achieve 0.4-dB Q^2-performance enhancement than the conventional TA-CE scheme with 800-km transmission in the presence of intra-channel nonlinearity, while avoiding increasing DSP complexity of channel acquisition and equalization for upgrading to 64-QAM format.

5. References

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