Nonlinearity-tolerant OSNR Monitoring Using Error Vectors and LSTM Networks in Coherent Optical Systems

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***Abstract*—Using error vectors as the inputs of LSTM networks, we estimate the OSNR of various signals after 400~1200km transmission and achieve <0.1dB mean absolute error in range of 23~33dB.**

Keywords—OSNR monitoring, Machine Learning, LSTM

I. Introduction

With optical networks evolving towards higher capacity and longer transmission distance, the system performance becomes less tolerant of transmission impairments [1]. OSNR is one of the most critical parameters to ensure robust, reliable network operation due to its direct relation with the signal quality. In digital coherent optical systems, receiver-DSP based OSNR monitoring can bring significant cost reduction compared to additional deployment of in-line monitoring devices [2] and get much attention.

Direct estimation of the OSNR in the frequency domain becomes difficult when the signal symbol rate approaches the channel spacing for higher spectral efficiency. Recently, several in-band OSNR monitoring techniques have been proposed, such as amplitude histograms [2], error vector magnitude (EVM) [3], delay-line interferometer [4], RF spectrum [5], amplitude noise correlation [6]. These methods achieve good accuracy but need additional feature extraction or aided-pilot. Machine Learning(ML) can make complicated linear and nonlinear compensation to provide better performance [7,8], but the data inputs and the ML models are still complicated, the OSNR accuracy at various distance and launch power need further studied through experiments.

In this paper, we demonstrate the error vectors have correlation across neighboring symbols and construct a LSTM network using the error vectors as inputs to estimate the OSNR. For 48Gbaud symbols (QPSK/16-QAM/64-QAM) transmitted over 400-1200km fiber in WDM scenario, the OSNR estimator achieves overall MAE (mean absolute error) <0.1dB in range of 23~33dB.

II. Principle

Fiber nonlinearity effects result in additional distortions, which is indistinguishable from ASE noise because they have similar distortions to the received signal distribution [8]. As the OSNR estimation is given by $OSNR_{estimated} = \frac{P_{in}}{P_{ASE}+P_{NL}}$, when the fiber nonlinearity cannot be neglected, the OSNR will be considerably underestimated[6].

The interaction of fiber nonlinearity, CD and ASE noise will produce distortions which are shown to be correlated across neighboring symbols even after appropriate linear impairment compensation. [6] demonstrates that the amplitude noise is correlated across neighboring symbols and is insensitive to ASE noise. [8] demonstrates the phase correlations are introduced by the interplay of dispersion and fiber nonlinearities. As originates from neighboring symbols, it is believed that the error vectors are also correlated and such correlations are largely attributed to nonlinear interactions between signal pulses.

In this paper we experimentally demonstrate the correlation between error vectors. Denoting Δ_k as the error vector of the kth received symbol, $\Delta_k = r_k - s_k$, where s_k is the transmitted M-QAM symbol and r_k the received symbol. Let the autocorrelation function (ACF) of error vectors across neighboring symbols be $R_\Delta(m) = E[\Delta_k \Delta_{k+m}]$, where $E[.]$ denotes expectation. We assume the received symbols are equalized and the carrier recovery are perfect. Error vectors and the ACF calculation are based on the normalized symbols. $|R_\Delta(1)|$ is used as the ACF because it has the largest correlation value, as is indicated in [6] and [8].

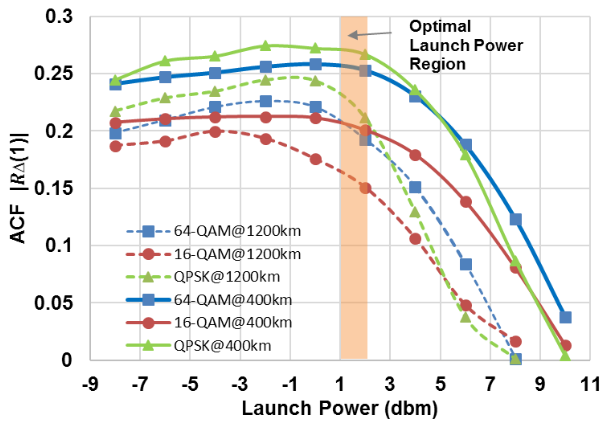

Fig.1. ACF vs Launch Power for different symbols after 1200km/ 400km transmission (single channel).

For demonstration, we transmit QAM symbols with single channel over 400km and 1200km fiber, the setup will be depicted later in Fig.3. As is shown in Fig.1, when we tune the launch power from -8 to 10 dbm, the ACF increases slowly when the launch power is moderate, but it decreases seriously when the launch power exceeds the optimal launch power region (1~2 dbm), the optimal launch power is estimated from the received SNR. It indicates that the correlation of error vectors decreases as the nonlinearity increase. For three modulation formats (QPSK/16-QAM/64-QAM), the ACF after 400km transmission (solid line) is larger than that of 1200km (dash line), since the signal deteriorates after longer transmission. When the launch power exceeds the optimal

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launch power region, the ACF of all formats decrease due to the influence of the fiber nonlinearity effect.

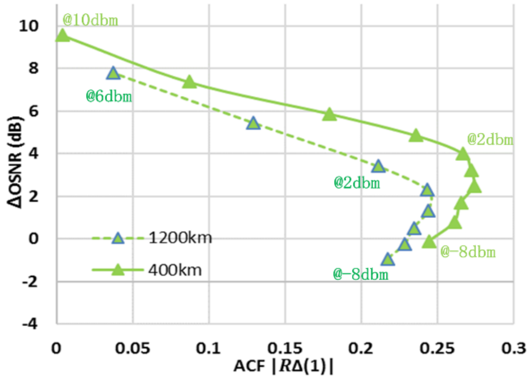

Fig.2 ΔOSNR vs ACF of QPSK.

We define the gap between the OSNR measured and the SNR as: $\Delta OSNR = OSNR_{measured} - \frac{R_s}{B_{ref}} SNR$. Fig.2 shows $\Delta OSNR$ vs the ACF of the QPSK signal, it reveals ΔOSNR and ACF linearly change with increasing launch power. As the LSTM network has memory and can make use of the delayed information across inputs, it is intuitive to expect the LSTM network can use the error vectors to estimate the ACF and $\Delta OSNR$, and approximate the actual OSNR.

III. EXPERIMENTAL SETUP

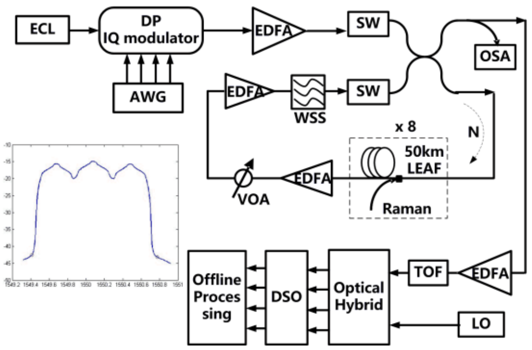

Fig.3. Experimental setup of 3x48Gbaud WDM transmission. Inset: spectrum with 50GHz spacing.

The experimental setup is depicted in Fig. 3. The modulated QAM symbols are generated with truly random number. After pre-equalization and resampling, 48-Gbaud polarization-multiplexed signal is transmitted with an arbitrary waveform generator (AWG, Keysight M9502A) operating at 92-GSa/s. Three ECL lasers work at 50GHz spacing (1546.12-1553.32nm), each is modulated with 45 GHz IQ modulator. The fiber loop consists of N×400-km G.654E fiber with Raman amplification. After the transmission, the balanced coherent receiver detects the optical signals, the real-time digital oscilloscope (DSO, Lecroy LM10-36Zi-A) records the dual polarization IQ signals with 80 GS/s.

As for the LSTM network, 2 successive LSTM layers are built, each layer contains 50 LSTM units, LeakReLU and dropout are used. MAE is chosen as the loss function and Adam optimization is applied for adaptive learning rate adjustment. The batch size and the training epoch are 100 and 150 respectively. The I_x , Q_x , I_y , Q_y before and after the symbol decision are used to calculate the error vectors $(\Delta_{Ix}, \Delta_{Qx}, \Delta_{Iy}, \Delta_{Qy})$ and the *SNR*. The transmission distance, which can be estimated from the taps of the DSP-based CD compensation filter, together with the modulation order *M* are also used as inputs of LSTM, as is shown in Fig.4. 23M QAM symbols are recorded at different launch power and distance, 30% of the dataset are used for test. The LSTM networks are built, trained, and tested in Keras with TensorFlow backend.

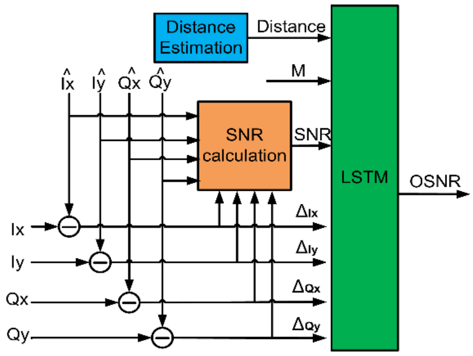

Fig.4. The inputs and output of LSTM network.

IV. RESULTS

We first demonstrate the ACF change with the launch power in the WDM scenario. As is shown in Fig.5, ACF decreases when the launch power exceeds the optimal value region, same as in the single channel scenario, although the optimal launch power of 1200km is much lower than that of 400km.

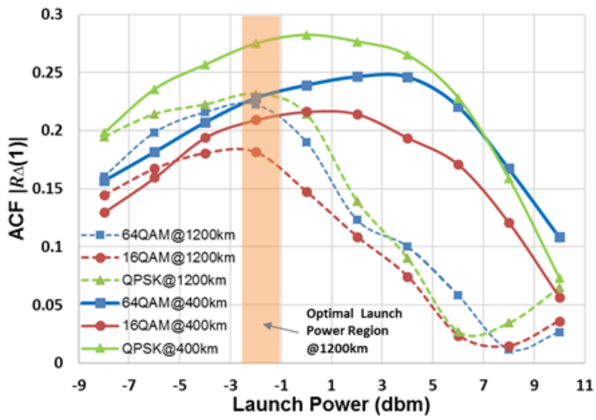

Fig.5. ACF changes with launch power after 400km and 1200 km transmission (3 WDM channel).

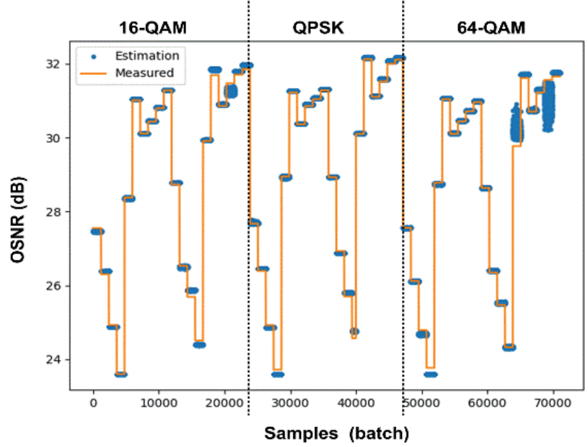

Fig.6. The OSNR measured and the OSNR estimated for the test sets.

Fig.6 shows the actual OSNR and the estimated OSNR in the test sets (>70000 batches). Most OSNR estimated match the OSNR measured in the range of 23-33dB. Fig.7 shows the MAE of OSNR estimation for 3 formats after 400km/1200km transmission. The overall MAE is 0.07dB and the max MAE value is 0.54dB. Fig.7(b) shows that after 1200km transmission, the MAE is smaller than that of 400km, and remains low at high launch power. Of three modulation formats, QPSK has stable MAE at different launch power and distance, this is partly due to its tolerance of high launch power.

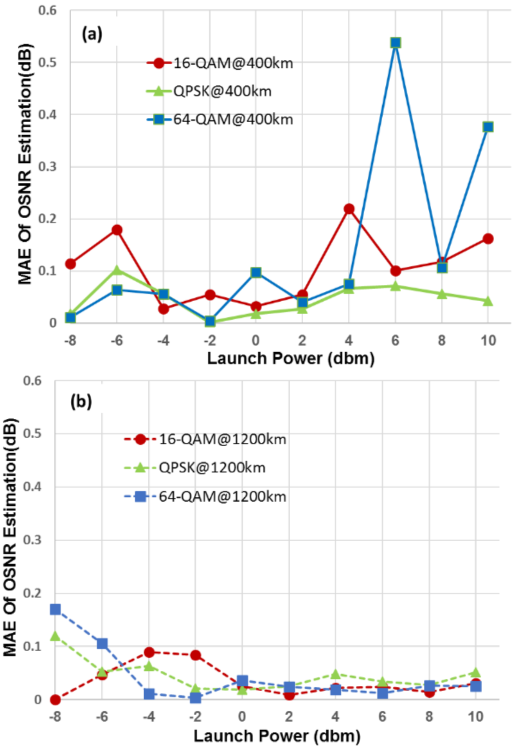

Fig.7. MAE of OSNR estimation vs launch power. (a) after 400km, (b)after 1200km.

V. Conclusions

We experimentally demonstrate the error vectors have correlation across neighboring symbols and construct a LSTM network using the error vectors as inputs to estimate the OSNR. Experiments demonstrate that the LSTM model achieve overall MAE<0.1dB in range of 23~33dB, the proposed OSNR estimator is nonlinearity-tolerant and works well in WDM scenario.

References

[1] Z. Dong, etc., "Optical Performance Monitoring: A Review of Current and Future Technologies," JLT, 34, 525-543(2016).

[2] M. S. Faruk, etc., "In-Band Estimation of Optical Signal-to-Noise Ratio from Equalized Signals in Digital Coherent Receivers," PJ, 6, 1-9 (2014).

[3] R. Schmogrow, etc., "Error Vector Magnitude as a Performance Measure for Advanced Modulation Formats," PTL, 24, 61-63 (2012).

[4] M. R. Chitgarha, etc., "Demonstration of in-service wavelength division multiplexing optical-signal-to-noise ratio performance monitoring and operating guidelines for coherent data channels with different modulation formats and various baud rates," OL, 39. 1605-1608 (2014).

[5] T. S. R. Shen, etc., "OSNR Monitoring for PM-QPSK Systems with Large Inline Chromatic Dispersion Using Artificial Neural Network Technique," PTL, 24, 1564-1567 (2012).

[6] Zhenhua Dong, etc., "OSNR monitoring for QPSK and 16-QAM systems in presence of fiber nonlinearities for digital coherent receivers," OE, 20, 19520-19534 (2012).

[7] Kashi, etc. "Nonlinear Signal-to-Noise Ratio Estimation in Coherent Optical Fiber Transmission Systems Using Artificial Neural Networks," JLT, 36, 5424-5431 (2018).

[8] T. Fehenberger, etc., "Experimental Analysis of Correlations in the Nonlinear Phase Noise in Optical Fiber Systems," in ECOC 2016, pp. 1-3.