Direct Nonlinear Noise Monitoring for In-Service Signals in Coherent Systems

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Abstract *Fibre nonlinear noise is directly monitored with the aid of an amplitude modulation pilot tone. For the first time, we demonstrate real-time, direct fibre nonlinear noise monitoring of in-service signals in coherent transceivers, with 0.2dB accuracy and 0.1dB sensitivity.*

Introduction

Optical performance monitoring is essential to achieve higher capacity by lowering the operating margin, and to reduce the operating expense by intelligent operation and maintenance. In coherent optical communication systems, fibre nonlinear interference (NLI) manifests itself as additive noise in dispersion uncompensated links. NLI is one of the major impairments limiting transmission capacity and reach. NLI monitoring has attracted a lot attention in recent years. Most of the monitoring methods proposed rely on the fact that the linear amplified spontaneous emission (ASE) noise is white, while nonlinear noise is somewhat "colored"[1]. Since the difference between ASE noise and NLI is subtle, and the NLI's "color" depends on link conditions, channel conditions etc., it is hard, if not impossible, to find a definitive algorithm to separate them. Instead, artificial neural networks (ANN) with machine learning (ML) have been used to perform the separation task.

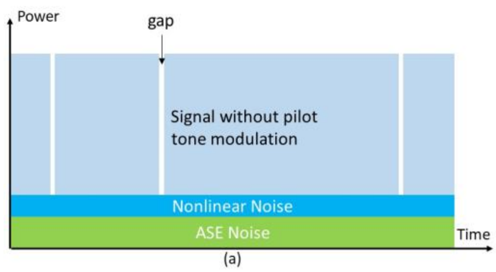
An artificial neural network model to estimate fibre nonlinear noise-to-signal ratio based on amplitude noise covariance of received symbols is presented in e.g., [2,3]. With NLI, the symbol/bit error becomes more bursty, which is reflected in the fast (short time window) BER distribution: it is therefore possible to use ANN/ML to extract the NLI[4,5]. NLI impacts the behaviour of the carrier phase recovery, hence from the recovered phase waveform, it is possible to learn and predict the NLI[6]. As is well-known, the accuracy of the ML model is ultimately determined by the quality and coverage of the training data. As it is impractical to collect all training data from measurements, training data are mostly generated from simulations. While those ANN/ML based methods show decent results under tested scenarios, direct monitoring is still highly desired.

We previously reported a direct nonlinear noise measurement method, with off-line experimental verification[7]. The method has since been implemented in the coherent transceiver's DSP ASIC chip. In this follow-up paper, we report its implementation and in-service real time experimental verification.

Principle

The working principle is shown in **Fig. 1**. Zero power gaps with a few symbols duration are inserted into the transmitted data signal. During propagation over the optical fibre link, both ASE noise and fibre nonlinear noise are added to the signal (**Fig. 1(a)**). Note that the gaps only contain the noise power, not the signal power. At first glance, it appears that the gaps should not contain nonlinear noise, because nonlinear noise is always associated with the signal. The reason why nonlinear noise is present also in the gaps is fibre dispersion. Propagating over a dispersive optical fibre, the gaps are quickly filled with energy from adjacent symbols; there are no gaps in the signal power waveform in majority of the fibre link, except at the very beginning. At the receiver, after the dispersion is removed, the gaps re-appear for the signal, and the nonlinear noise is left in the gaps[7].

To monitor the nonlinear noise, we need a mechanism to distinguish the nonlinear noise from the ASE noise. A relatively low-frequency (in kHz/MHz range) amplitude modulation, referred to as amplitude modulation pilot tone (PT), is applied to the high-speed signal (a few tens of GBd). Since the nonlinear noise follows the signal's local power, it is also modulated by the PT. On the other hand, the ASE noise is generated by the link optical amplifiers, and is not affected by the PT (**Fig. 1(b)**). Therefore by detecting the PT modulated noise in the gaps, pure nonlinear noise can be measured.



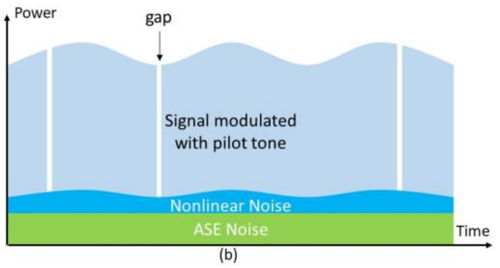


Fig. 1. Nonlinear noise monitoring principle.

Implementation

The amplitude modulation pilot tone is digitally implemented in the coherent transmitter's DSP without any hardware cost. Assuming $V_0(t)$ is the original time domain voltage without PT, the following operation applies PT to the signal:

$$V_{\mathrm{PT}}(t) = V_0(t)(1 + m\sin(2\pi f_{\mathrm{PT}} t)), \qquad (1)$$

where f_{PT} is the pilot tone frequency, $m \ll 1$ is related to the modulation depth. For dual polarization QAM signals, there are 4 data streams (two orthogonal polarizations and in-phase and quadrature phase), therefore the above equation may be applied to all of them. This operation is done in the Tx DSP before sending to the DAC to drive the modulator.

Fig. 2 shows the how multi-band PT is implemented in Tx DSP[8]. With multi-band PT, different modulations may be applied to different signal spectra to achieve more advanced monitoring functionalities, such as signal spectrum and filtering monitoring. For the purpose of this work, multi-band PT is not required, so the same pilot tone modulation is applied to all signal spectral components. It is interesting to note that the nonlinear noise is usually colored with a stronger low frequency component, so multi-band PT could be used to measure nonlinear noise's spectral distribution.

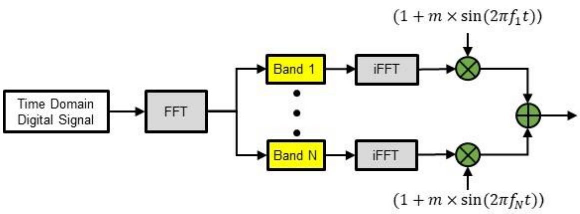


Fig. 2. Multi-band amplitude modulation pilot tone Generation in transmitter DSP.

The detection of the nonlinear noise is implemented in the coherent receiver's DSP. **Fig. 3** shows a typical coherent receiver's block diagram, the monitoring block is after all conventional DSP functionalities are done to remove linear impairments, and just before the symbol decision block. In order to measure the nonlinear noise properly, the pilot tone power P_{PT} outside the gaps, and the pilot tone power in the gaps $P_{\mathrm{gap,PT}}$ are required.

Assuming $E(t)$ - the received, equalized optical electrical field - $P(t) = |E(t)|^2$ is the signal power waveform. $P(t)$ is modulated by PT; it is related to the un-modulated signal $P_0(t)$ by,

$$P(t) = P_0(t)(1 + m' \sin(2\pi f_{\mathrm{PT}} t)). \qquad (2)$$

We need to find the average power $\overline{P_0(t)}$ outside and inside the gaps, which correspond to the signal power P_{PT} and the nonlinear noise power $P_{\mathrm{gap,PT}}$, respectively.

In order not to change the DSP frame structure, the reserved, un-used symbols in the DSP frame are used to achieve the gaps. The gaps are therefore scarce, non-uniform, and less frequent than the PT period. The FFT spectrum analysis method cannot be used for measuring the PT amplitude. Note that the PT modulation is generated digitally in the Tx DSP, and the detection is done in the Rx DSP; the Tx and Rx clocks are accurately synchronized once the Rx works normally. We can generate a sinusoid function in Rx DSP with an exact PT frequency, and use this sinusoid function to extract the PT amplitude by correlation operation:

$$A_{PT} = \overline{P(t)(1 + m\sin(2\pi f_{\mathrm{PT}} t))\sin(2\pi f_{\mathrm{PT}} t)}\ . \qquad (3)$$

This PT amplitude is P_{PT} if $P(t)$ outside the gaps is used for the calculation; it is $P_{\mathrm{gap,PT}}$ if $P(t)$ inside the gaps is used.

The nonlinear OSNR is then given by

$$\mathrm{OSNR}_{\mathrm{NLI}} = \frac{P_{\mathrm{PT}}}{P_{\mathrm{gap,PT}}} \frac{f_b}{BW_{Ref}}, \qquad (4)$$

where BW_{Ref} is the reference bandwidth in the OSNR definition, which is usually 0.1nm or about 12.5GHz in the C band, f_b is the signal baud rate. Interestingly, the PT's modulation depth is not required as this is a relative measurement.

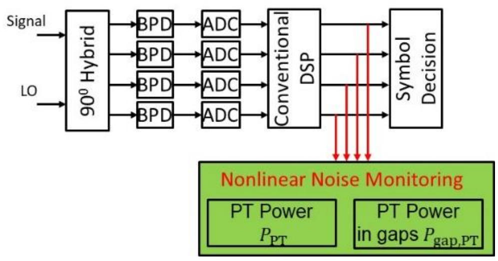


Fig. 3. The nonlinear noise monitoring block is performed in Rx DSP after all equalization and before symbol decision. BPD: balanced photodetector, ADC: Analog-to-Digital converter.

Experimental Demonstration of Real-Time Direct Nonlinear Noise Monitoring

Fig. 4 depicts the experimental setup for the demonstration of the nonlinear noise monitoring performance. Forty loading channels co-propagate with the testing channel over the fiber link. All the channels are generated with individual real-time coherent transceiver line cards. The transmission BER performance and nonlinear noise power monitoring are measured with a coherent transceivers that with advanced ASIC DSP processor that enables high capacity FEC and nonlinear noise monitoring. The dispersion un-compensated link is comprised of multiple 80km fibre (either LEAF or SSMF) spans. A wavelength selective switch (WSS) module is used every 6 spans or so to equalize the channel powers. As comparison, the standard BER vs. OSNR measurements are also performed to extract the “actual” nonlinear noise. To perform BER vs OSNR measurement, ASE noise is loaded at the Rx to vary OSNR. Note that ASE loading at Rx is not required for the proposed nonlinear noise monitoring approach.

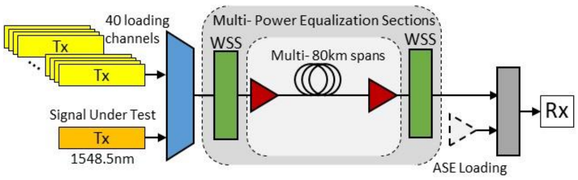


Fig. 4. Experimental setup.

Fig. 5 plots the monitored OSNR penalty versus fiber launch power for transmission over 20 span LEAF, 25 span SSMF, and 12 span SSMF links. The solid curves (marked with “PT”) are OSNR penalties predicted from the nonlinear noise power monitored by the transceiver DSP. The dashed curves (marked with “BO”) are the measured OSNR penalty with standard BER~OSNR method. A good agreement is obtained between these two methods, with a difference of less than 0.2dB.

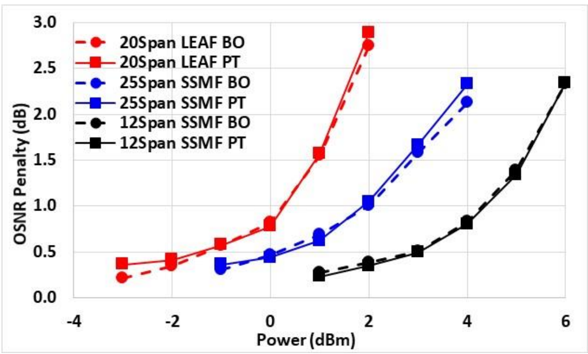


Fig. 5. Experimental results.

To demonstrate the real time monitoring capability and sensitivity, three groups of different channel loading and fibre launch power experiments are performed for the 25 SSMF span link. In group #1 (Test # 1-5 in **Fig. 6**), the power of all the channels is mostly even, and the channel power is roughly varied from 2.3 dBm to 3.1 dBm with small step size. In group #2 (Test # 6-9 in **Fig. 6**), the testing channel power is initially set at about 2 dBm (Test #6), and the powers of the two adjacent channels are gradually increased while keeping the power of all other channels unchanged. In group #3 (Test # 10-12 in **Fig. 6**), the loading channels are changed to channels 1-20 and 61-80 so that the XPM is greatly reduced and the nonlinear noise is mostly from SPM. The signal power is then changed to have different nonlinearity. The measured OSNR penalties using the proposed method are shown in the red squares (PT). As comparison, the measured results using the standard BER~OSNR method (BO) are also shown (blue circles). As is seen, the proposed method can monitor as small a change as 0.1dB nonlinear penalty.

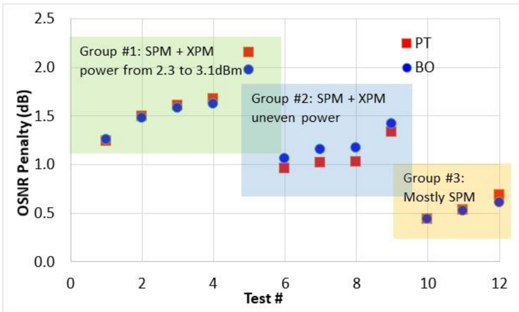


Fig. 6. Demonstration of nonlinearity induced OSNR penalty monitoring sensitivity. As small as 0.1dB OSNR penalty change can be measured in real time.

Conclusions

For the first time, real-time, direct nonlinear noise monitoring has been achieved in a product coherent transceiver. The accuracy is excellent with better than 0.2 dB accuracy and 0.1 dB sensitivity, much better than any published results. This unprecedented accuracy is much needed for adaptive optical networks where accurate online QoT (Quality of Transmission) monitoring is essential.

An interesting note: since different PTs can be applied to signals of different polarization, and to different signal spectra, we should be able to achieve polarization-resolved and spectrum-resolved nonlinear noise monitoring. They will be explored in future.

References

[1] Z. Dong *et al*., “OSNR Monitoring for QPSK and 16-QAM Systems in Presence of Fiber Nonlinearities for Digital

Coherent Receivers," *Optics Express*, Vol. 20, no. 17, p.19520 (2012).

[2] A. S. Kashi *et al*., "Fiber Nonlinear Noise-to-Signal Ratio Monitoring Using Artificial Neural Networks," ECOC 2017, M.2.F.2.

[3] Andrew D. Shiner *et al*., "Neural Network Training for OSNR Estimation From Prototype to Product," OFC 2020, M4E.2.

[4] Ali Salehiomran *et al*., "Linear and Nonlinear Noise Monitoring in Coherent Systems Using Fast BER Measurement and Neural Networks," ECOC, Dublin, September 2019, W.3.D.3.

[5] Ali Salehiomran *et al*., "Fast BER Distribution and Neural Networks for Joint Monitoring of Linear and Nonlinear Noise-to-Signal Ratios," OFC 2010, M2J.3.

[6] Daniel Lippiatt *et al*., "Joint Linear and Nonlinear Noise Estimation of Optical Links by Exploiting Carrier Phase Recovery," OFC 2020, Th2A.49.

[7] Zhiping Jiang *et al*., "Nonlinear Noise Monitoring in Coherent Systems Using Amplitude Modulation Pilot Tone and Zero-Power Gap," OFC 2019, Th2A.34.

[8] Zhiping Jiang and Xuefeng Tang, "Low-Cost Signal Spectrum Monitoring Enabled by Multiband Pilot Tone Techniques", ECOC 2018, We2.41, 2018.