Spectrum Resolved SNR Monitoring of In-Service Channel

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Abstract: We propose and experimentally demonstrate a novel scheme to monitor the spectrum resolved SNR with receiver ADC buffer data. SNR accuracy of 0.2dB can be achieved, and filtering impact can be separated from link noise. © 2024 The Author(s)

1. Introduction

Performance monitoring plays an important role to ensure the optical network is operated properly and optimally, especially with the desire to squeeze operating margin [1]. There has been extensive research on performance monitoring [2]; however, so far there are very few reports on spectrum resolved monitoring.

As the baud rate increases, the signal-to-noise ratio (SNR) within the signal bandwidth is no longer flat. An analytical expression was derived for optical SNR (OSNR)-aware digital pre-emphasis for high baud rate coherent optical transmissions, assuming white transceiver noise within the signal bandwidth [3]. Knowledge of the true noise spectrum would help to achieve better performance. Waveform correlation method has been used for detecting the generalized OSNR along the link with a dedicated coherent detector [4,5]. Error vector magnitude (EVM) has been an effective metric for optical channels limited by additive white Gaussian noise [6]. However, they are not spectrum resolved and cannot separate the filtering introduced intersymbol interference (ISI) from the link noise.

In this paper, we propose to use the correlation between the received noisy waveform and the re-constructed pure signal waveform in frequency slices to monitor the spectrum resolved SNR at the receiver (Rx) for in-service channels. Experiments show that the SNR monitoring error is less than 0.2 dB, and it can separate the filtering effect from other link impairments such as ASE and nonlinear noise contributions. The proposed scheme can be applied to the root cause analysis (RCA) for soft failures in optical networks, and no additional hardware is required.

2. Monitoring Principle

The total field waveform $E_{tot}(t)$ at the Rx can be expressed as $E_{tot}(t) = E_s(t) + E_n(t)$, where $E_s(t)$ and $E_n(t)$ are the signal and noise field waveforms, respectively. The field waveforms can be converted to frequency domain using fast Fourier transform (FFT), then the spectrum can be sliced into spectral width Δf, and converted back to time domain by inverse-FFT to obtain the spectrum resolved waveforms $E_{tot}(f,t)$ and $E_s(f,t)$ at frequency f (see Fig. 1). A normalized correlation parameter can be defined as

$$CORR(f) \equiv \frac{\langle E_{tot}(f,t) E_s^*(f,t)\rangle}{\sqrt{\langle |E_{tot}(f,t)|^2\rangle}\sqrt{\langle |E_s(f,t)|^2\rangle}} = \frac{P_s(f)}{\sqrt{P_s(f)+P_n(f)}\sqrt{P_s(f)}} = \frac{1}{\sqrt{1+1/SNR(f)}}, \quad (1)$$

where $\langle \quad \rangle$ is the expectation operator, $P_s(f) = \langle |E_s(f,t)|^2\rangle$ and $P_n(f) = \langle |E_n(f,t)|^2\rangle$ are the signal and noise powers at frequency f with spectral width Δf, respectively. Because there is no correlation between signal and noise, the cross terms between signal and noise waveforms are averaged to zero, and hence $\langle |E_{tot}(f,t)|^2\rangle = P_s(f) + P_n(f)$. The signal-to-noise ratio is $SNR(f) = P_s(f)/P_n(f)$. The spectrum resolved SNR is then given by

$$\frac{1}{SNR(f)} = \frac{1}{CORR^2(f)} - 1. \quad (2)$$

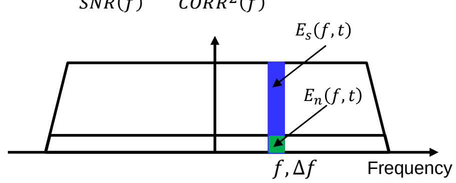

Fig. 1 Spectrum resolved waveforms at frequency f with spectral width Δf.

The above described SNR monitoring scheme requires pure signal and signal+noise electrical field waveforms, which can be easily obtained in the coherent Rx. Fig. 2 shows a coherent Rx diagram with the proposed spectrum resolved SNR monitoring capability. After the balanced photodetectors (BPD), 4 analog to digital converters (ADC) convert 4 data streams into digital domain. After proper DSP blocks (chromatic dispersion compensation, frequcency offset compensation, equalizer, timing recovery, carrier phase recovery and so on), total waveforms (signal+noise) are obtained at ① for two orthogonal polarizations. The transmitted data can be obtained by hard decision at ②, and are used to re-construct the pure signal waveforms. The spectrum resolved SNR can then be calculated by Eq. (2).

The proposed method relies on the assumption that the re-constructed signal waveform at ② is the same as the signal in the noisy waveform at ①. As the transmitter (Tx) signal passes through various transfer functions, such as Tx digital pre-emphasis, DAC, driver, optical link, Rx OE front-end and ADC, it is impossible to get the accurate overall channel response and obtain accurate signal waveform re-construction as received at ①. In other words, the re-constructed signal $E_s'(t)$ will not be exactly the same as $E_s(t)$ in $E_{tot}(t)$, and the discrepancy will lead to monitoring error. Interestingly, this is not a problem in the spectrum resolved SNR monitoring: as long as the overall channel response is flat within the spectral slice Δf, the re-constructed spectrum resolved waveform $E_s'(f,t)$ will be the same as $E_s(f,t)$ in $E_{tot}(f,t)$. The proposed method can identify different causes of impairments, such as filtering and link noise. Not shown in this paper, but for polarization multiplexed signals, the SNRs for both polarizations can be estimated individually, and thus polarization dependent loss (PDL) could also be identified.

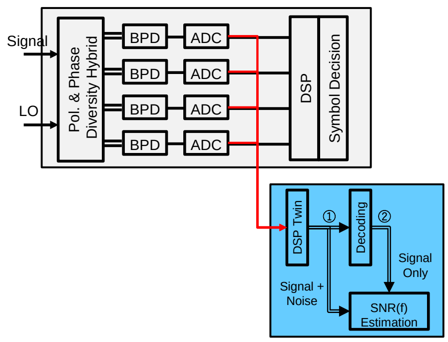

Fig.2 Schematic of spectrum resolved SNR monitoring at the coherent Rx.

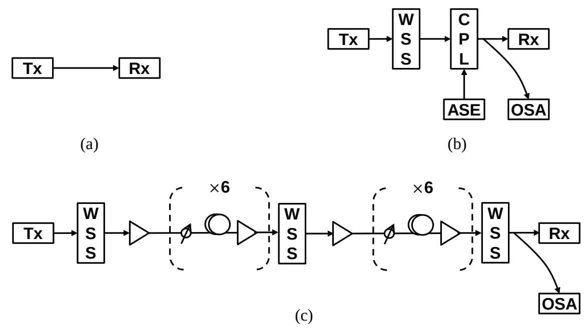

Fig.3 Experimental setup. (a) Back-to-back (B2B). (b) B2B with ASE loading. (c) 12-span link.

3. Experimental Demonstration

The experimental setup is shown in Fig. 3. In Fig. 3(a), the Tx and Rx were directly connected to measure the transceiver noise. In Fig. 3(b), flat amplified spontaneous emission (ASE) noise was added to the signal by a coupler (CPL); a flex-grid wavelength selected switch (WSS) with 3.125GHz resolution was inserted in the signal path to shape the signal spectrum, and therefore the noise-to-signal ratio (NSR) spectrum of the ASE. An optical spectrum analyser (OSA) was used to monitor the signal and ASE spectra. A commercial 400Gbps 16QAM transceiver with baud rate of 68.5G was used in the experiment. The Rx was equipped with ADC buffering capability: continuous 32k ADC data samples could be captured for offline processing. Conventional Rx DSP was applied to this ADC buffer before the spectrum resolved SNR was calculated.

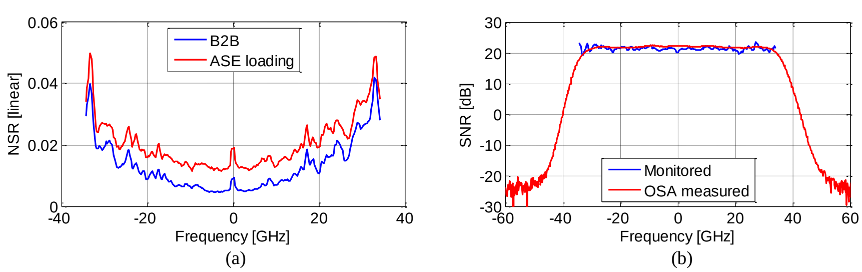

Fig. 4 (a) Estimated transceiver noise spectrum (blue) and noise spectrum with ASE loading (red). (b) OSA measured signal-to-ASE ratio (red) and estimated by the proposed method (blue).

Fig. 4(a) plots the NSR spectrum for the transceiver only (B2B, blue) and with ASE noise loading (red) cases. The spectral resolution is 1 GHz. As expected, the transceiver noise increases drastically as frequency increases, and periodic clock tones can be seen at the peaks. By subtracting the transceiver noise from the total noise with ASE loading, the ASE noise can be obtained (Fig. 4(b) blue). Good agreement is achieved between the OSA measurement (Fig. 4(b) red) and the estimation by the proposed method.

Next, the proposed method was verified with the signal propagating through a link of 12 spans each consisting of 75 km single mode fiber, as shown in Fig. 3(c). 200Gbps QPSK with baud rate of 68.5G was transmitted. Two experiments were performed here. First, the launch power into the fiber was varied from -6 dBm to 3 dBm with a step of 1 dBm, and Rx ADC buffer data and the corresponding Rx pre-FEC BER were recorded. The SNR of the received signal here included both ASE noise and fiber nonlinear noise, and was calculated by averaging the spectrum resolved NSR in linear unit and then taking the inverse. For comparison, the SNR was also generated from the Rx pre-FEC BER using the relation $BER = \frac{1}{2}\mathrm{erfc}\left(\sqrt{\frac{EC/2}{NSR}}\right)$, where EC is the eye-closure factor which is close to 1 and can be calibrated by a B2B with ASE loading measurement using OSA. Fig. 5(a) plots the Rx pre-FEC BER versus the SNR calculated with our proposed method (red crosses) and the BER-SNR curve from B2B measurement (blue line). Fig. 5(b) shows that the SNR difference is less than 0.2 dB between the two methods.

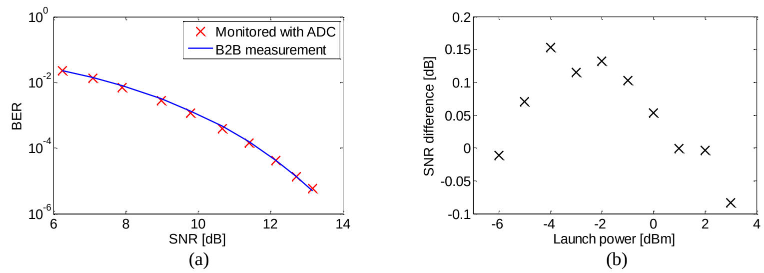

Fig. 5 (a) Rx pre-FEC BER versus the SNR calculated from ADC data (red crosses) and from B2B measurement (blue line). (b) SNR difference between two methods.

In the second link experiment, the first WSS bandwidth was changed between 62.5 GHz and 100 GHz, the launch power was 3dBm, and again Rx ADC buffer data and the corresponding pre-FEC BER were recorded. The narrow WSS filter imposes penalty on BER and corresponding SNR, as shown in Fig. 6(a) and (b), respectively. The SNR penalty calculated from BER is 0.6 dB at 62.5 GHz WSS bandwidth, including both ISI and link noise contributions. However, with our proposed method, the central part of the SNR spectrum calculated from ADC buffer data is not impacted by the filter narrowing, but only the SNR spectrum edges are shaped by the filter, as depicted in Fig. 6(c). Hence, the filtering effect can be differentiated from other link impairments.

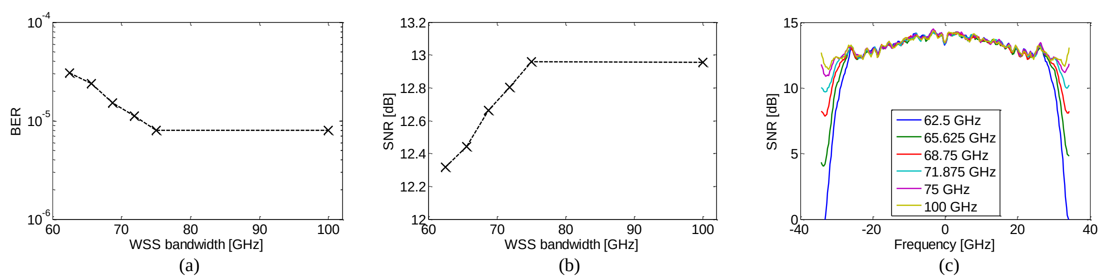

Fig. 6 The first WSS bandwidth is reduced. (a) Rx pre-FEC BER. (b) SNR calculated from the pre-FEC BER. (c) SNR spectrum calculated with the proposed method.

4. Conclusion

To the best of our knowledge, this is the first time that spectrum resolved SNR monitoring at the Rx is reported. The scheme only requires Rx ADC buffer data, which is widely available with commercial coherent receivers and does not cost extra hardware. We experimentally demonstrated in a 12-span link that the SNR monitoring error was below 0.2 dB with a wide range of launch powers, and this method could separate filtering impact from link noises. The proposed scheme can be applied to the root cause identification for soft failures in optical networks. And this monitoring could also enable better Tx pre-emphasis and link inband SNR equalization, especially for high baud rate transceivers.

5. References

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