Fast Optical Performance Monitoring for Diagnosing Transient Behavior during Channel Add/Drop

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Abstract *Fast (millisecond scale), receiver DSP-based optical performance monitoring of key parameters, such as OSNR, fiber nonlinearity, BER, and power, is demonstrated and used in diagnosing the transient behavior during channel add/drop.*

Introduction

Wavelength division multiplexed optical communication systems are complicated analog systems, involving a large number of transmission impairments. Optical performance monitoring (OPM)[1] is essential to achieve higher capacity by accurately allocating just enough operating margin, and to reduce the operating expense by intelligent operation and maintenance, such as fast fault identification and localization.

OPM has been widely used in failure identification and localization. For example, the time series of the pre-FEC (forward error correction) BER (bit error rate) and received power are used for optical filtering-related failure identification and localization[2]. Channel add/drop operation occurs routinely in optical networks, it may cause significant and fast performance degradation on the existing/remaining channels. Recently we developed a coherent receiver DSP based capability for direct fiber nonlinear noise monitoring of the in-service signal, with unprecedented accuracy[3,4]. As monitoring speed is important when dealing with transient effects, in this paper, we show that it can be done in millisecond time scales. Along with other DSP-based performance monitoring capabilities, we demonstrate the application of these fast real-time performance monitoring in understanding the transient behavior during channel add/drop.

Fast Real-Time Performance Monitoring in Receiver DSP

With powerful DSPs, modern digital coherent receivers can be used to monitor optical performance, without additional hardware costs. For example, the accumulated chromatic dispersion (CD) can be estimated from the chromatic dispersion compensation block, and the change rate of the state of polarization (SOP) and the differential group delay (DGD) can be estimated from the 2x2 MIMO equalizer[5]. Performance monitoring concerns a long list of parameters; however, in this section, we describe only those that are critically relevant to the demonstration in the next section.

ASE and NLI noise monitoring: The amplified spontaneous emission (ASE) noise from the link optical amplifiers and the fiber nonlinear interference (NLI) due to Kerr nonlinearities are arguably the two most important impairments in fiber communication systems. In dispersion-uncompensated links, the NLI can be treated as additive white Gaussian noise (AWGN). The monitoring of ASE (or OSNR) and nonlinear noise is not trivial and has attracted a lot attention in recent years. The main difficulty is to separate nonlinear noise from ASE noise. Artificial neural networks with machine learning have been widely used to perform the separation task.

Recently, we developed a direct nonlinear noise monitoring capability for the in-service signal. Zero-power gaps are introduced to monitor the link noise. Additionally, with an amplitude modulation pilot tone on the signal, the nonlinear noise is also modulated while the ASE noise is not. In this way, both the ASE noise and nonlinear noise can be directly monitored. Nonlinearity penalty can be monitored for the in-service signal with excellent accuracy and sensitivity[3]. Since then, we have optimized the noise monitoring algorithms, and the reporting speed is improved from tens of seconds to milliseconds. Therefore they can be used in diagnosing transient behavior, as shown in the next section.

BER monitoring: Forward error correct (FEC) is used in modern optical communications. The BER (bit error rate) before FEC (pre-FEC BER) must be kept below a certain threshold so that the BER after FEC decoding (post-FEC BER) is zero (or less than 10^{-15}). BER is a basic performance parameter that is reported in the receiver FEC decoder. The reported BER is usually averaged over a long period, such as 1 second. The

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minimum, average, and maximum BER over longer intervals, such as 15 minutes, may also be logged. While critical in knowing the signal's quality, important information is lost in this kind of long-term averaged BER. We have shown that fast (nanosecond time window) BER statistics can be used to separate the fiber nonlinear noise and ASE noise[6]. In this paper, we show that millisecond BER reporting is critical in understanding transients.

Signal power monitoring: The monitoring of the received signal power is straight forward, especially for relative power monitoring. In coherent receivers, RF amplifiers with automatic gain control (AGC) are usually used. The gains of the AGCs are controlled in such a way that the signal levels into the following ADCs (analog-to-digital converter) are properly maintained. The received signal power can be derived from the AGC gain and the signal level in the DSP.

Demonstration of Real-Time Performance Monitoring During Channel Add/Drop

EDFAs (Erbium Doped Fiber Amplifiers) are used to compensate the losses from transmission fiber and other components. It is well-known that the spectral gain profile of an EDFA is a complicated function of channel loading (the number and spectral locations of the channels)[7]. Channel loading changes during channel add/drop, which may happen in scenarios such as system expansion, channel re-route, and fiber cut. Although the gain change in one EDFA is relatively small (a fraction of a dB), channel add/drop can lead to very large (many dBs) power excursion on the existing/remaining channels, due to the fact that a fiber link may contain tens of EDFAs.

Power change affects a signal's performance through OSNR and fiber nonlinearity change. The experimental setup in Fig. 1(a) is used to demonstrate real-time performance monitoring during channel add/drop. The system consists of 8x80km SSMF spans, and a wavelength selective switch (WSS) at the link head-end is used to combine the signal channel under test as well as the loading channels, and to equalize the channel powers. The signal channel is polarization-multiplexed 400Gbps 16 QAM at 1531.4nm. The loading channels are divided into two groups: one group emulates the channel add/drop operation, and the other group is not altered during the experiment. To mimic fast add/drop in scenarios like fiber cut, and optical switch-based channel re-route for traffic restoration, instead of using the WSS directly, a variable optical attenuator (VOA) is used in the add/drop group to pass/block the channels, allowing faster channel add/drop than possible by WSS. For easy demonstration, the VOA is operated at very high loss (block) and very low loss (pass) state, so the channels are repeatedly added/dropped. The unequal VOA block and pass times (1.0 and 0.6 seconds, respectively) are used to distinguish the conditions. The power spectrum at the end of the link (just before the last WSS) is shown in Fig. 1(b), showing significant power excursion on the test channel.

A few things happen during channel add/drop: 1) largely due to channel loading-dependent EDFA gain profile changes, the signal channel experiences power changes before and after the channel add/drop, leading to OSNR and SPM (self-phase modulation) noise changes; 2) XPM (cross-phase modulation) noise changes - there is more/less XPM noise in the add/drop state; 3) power transients (overshoot, undershoot) during the transition from add to drop state or drop to add state. This transient occurs if the EDFA gain control is not fast enough to track its input power change.

Fig. 2 shows the time series of the received signal power, the total/nonlinear noise (normalized by the signal power), and BER at 3 channel powers at the fiber input: 5, 3, and 1 dBm. The plotted

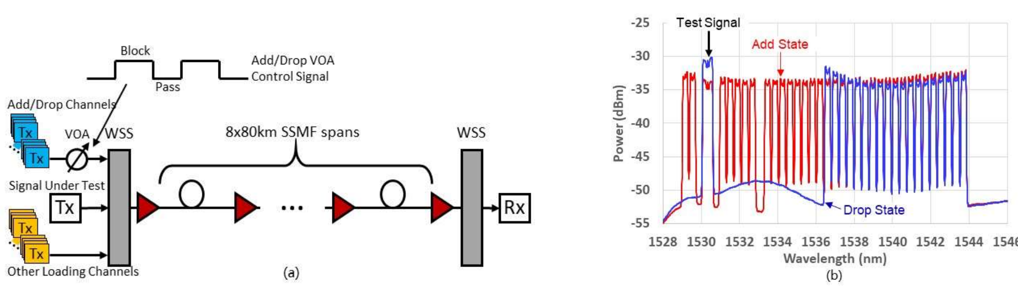

Fig. 1: (a) Experimental setup. (b) Spectrum at link egress, showing significant power excursion on the test signal. Blue curve: channel add (VOA pass), red curve: channel drop (VOA block).

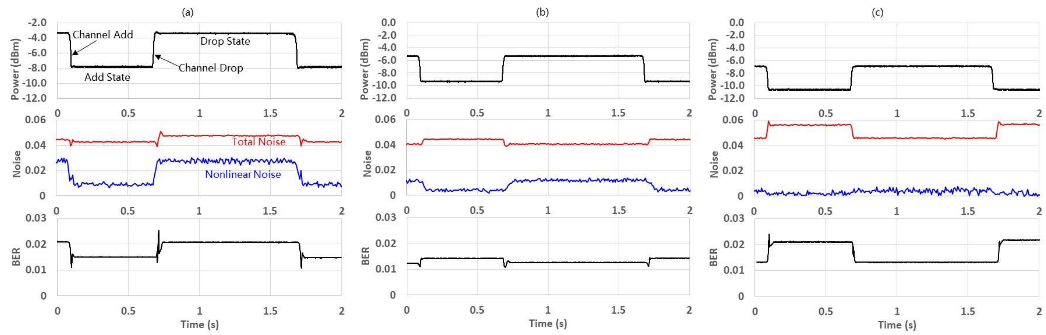

Fig. 2: Real-time performance monitoring during channel add/drop. Per-channel launch power is (a) 5 dBm, (b) 3 dBm, and (c) 1 dBm.

measurement window is slightly more than one add/drop cycle. We could achieve sub-ms temporal resolution on the power, total noise and BER monitoring, and about 10ms resolution on the nonlinear noise monitoring. The nonlinear noise monitoring speed could be further improved to sub-ms in the future. When adjacent channels are added/dropped, the signal channel gain decreases/increases due to the EDFA's spectral hole burning effect, leading to lower/higher received signal power. The total noise may be lower or higher depending on the link operating condition. With high channel power, the total noise is lower in the add state (Fig. 2(a)), whereas the total noise is higher in the add state with low channel power (Fig. 2(b) and (c)). This is because fiber nonlinear noise dominates in the high channel power scenario.

the optimal operating point. Using the experimental setup in Ref. [3], the ASE, nonlinear noise, and BER are monitored as the function of channel power into the fiber (Fig. 3(a)). As expected, the ASE noise decreases with the channel power, while the nonlinear noise increases. The BER is also plotted. As is well-known, the optimal condition is when the ASE noise is twice the nonlinear noise, which is confirmed in Fig. 3(a).

We also observed post-FEC error alarm during channel add/drop even if the steady state BER is below the FEC threshold. The fast BER waveform is plotted in Fig. 3(b), showing that the instantaneous BER exceeds the FEC threshold at the transition (red circled).

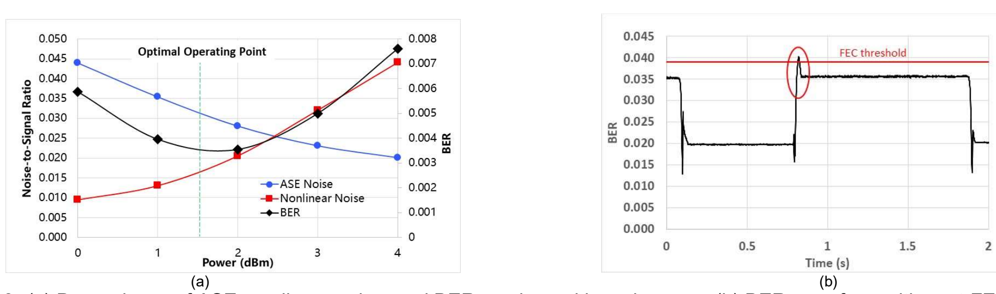

Fig. 3: (a) Dependency of ASE, nonlinear noise, and BER on channel launch power. (b) BER waveform with post-FEC error alarm.

The BER waveform is consistent with the total noise waveform, which is confirmed by converting the total noise waveform into a BER waveform using the calibrated BER vs. total noise curve (not shown here due to space limitations). The overshoot/undershoot at the transition is due to EDFA transients, which could lead to additional performance degradation vs. the steady state. Better transient suppression is required to eliminate this kind of transient performance degradation.

It is noticed that the total noise/BER is lower in Fig. 2(b), which can be explained as representing

Conclusion

Taking channel add/drop as an example, we have demonstrated the application of millisecond-scale performance monitoring to understanding performance changes, and fault identification. As the optical network is becoming more dynamic and the operating margin is squeezed to improve the network efficiency, optical performance monitoring is playing an ever more important role in assuring reliable operation and fast traffic recovery in the event of faults. We emphasize the importance of performance monitoring speed in detecting transient phenomena.

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