DSP Enabled, Amplitude Modulation Pilot Tone Based Optical Performance Monitoring in Coherent Systems

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Abstract *We review the progresses of amplitude modulation pilot tone generation and detection techniques and its applications in optical performance monitoring, such as signal spectrum, optical filtering, and fiber nonlinearity.*

Introduction

Wavelength division multiplexed (WDM) 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.

Optical filtering and fiber nonlinearity are two major impairments, however their monitoring is not trivial. There have been extensive studies in optical filtering related failure identification and localization[2-4], and in the separation of fiber nonlinear noise from ASE noise[5-9]. Due to the lack of direct, low cost monitoring capability, many of these studies involve machine learning.

In this paper, we review the progresses of amplitude modulation pilot tone (AM-PT) based optical performance monitoring technique and its applications in monitoring the signal spectrum, optical filtering, and fiber nonlinearity.

Multi-band Amplitude Modulation Pilot Tone and its Application in Signal Spectrum and Optical Filtering

Amplitude modulation pilot tone based optical performance monitoring has existed for a long time[10-11]. In its simplest form, each wavelength is applied a small and unique amplitude (power) modulation at relatively lower frequency compared to the high speed data modulation. For detection, a small portion of light is tapped, and converted into electrical signal by a photodetector. Spectrum analysis is performed in electrical domain, the amplitude of each pilot tone is proportional to the optical power of the corresponding wavelength (Fig. 1). This provides per channel power monitoring without wavelength demultiplexing. The detection only requires a photodetector and digital signal processor (DSP), therefore it is a low cost solution (Fig. 2). The pilot tone detector (PTD) can be massively deployed throughout the entire optical network. In addition, PT can be turned on-off to encode channel specific information (central wavelength, baud rate, modulaton format, source and destination nodes and so on), which is very useful for network operation.

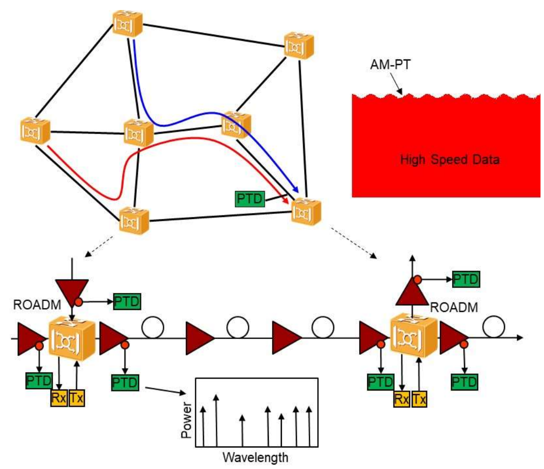

Fig. 1: AM-PT provides a low cost solution for channel monitoring. PTD: pilot tone detector.

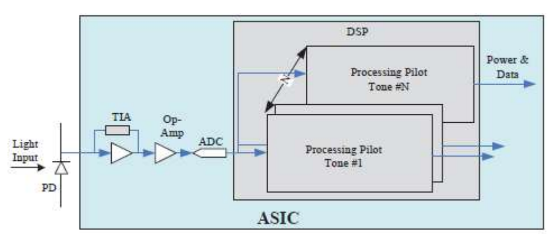

Fig. 2. Pilot-tone detector consists of a low speed (MHz) photodetector (PD), pre-amp (TIA), op-amp, analog-to-digital converter (ADC) and digital signal processor (DSP), which can detect all N pilot tones. All except the PD has been implemented in a 6x6 mm^2 ASIC chip.

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With conventional pilot tone, the entire wavelength channel is applied the same modulation, it is not possible to do sub-channel monitoring. Thanks to Tx DSP, different modulation can be applied to different signal spectrum[12] (Fig. 3). This multiband pilot tone technique allows for sub-channel monitoring.

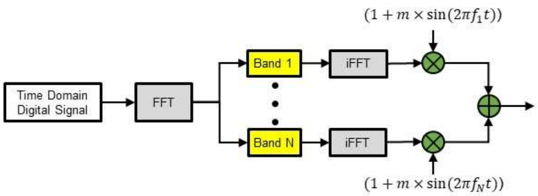

Fig. 3: Multiband pilot tone generation in digital domain. The time domain signal is converted to frequency domain by FFT, and each FFT bin is applied a different PT and recombined to generate multiband PT.

Multiband PT can be used to monitoring signal spectrum with very high (sub-GHz) resolution. Examples are shown in Fig.4, the spectrum obtained by PTD is better resolved than that by OSA of 0.03nm resolution [13].

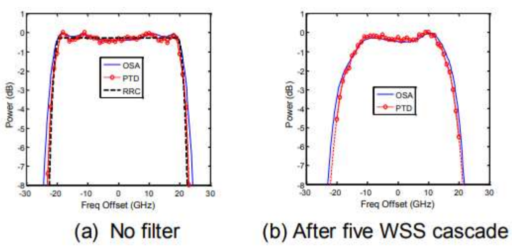

Fig. 4: Signal spectrum measured by a conventional OSA and the multiband pilot tone technique.

When two different pilot tones are applied to a signal's positive and negative spectral bands, the power difference monitored by these two pilot tones is an indication of relative frequency offset between signal and optical filter. Therefore, this dual-band pilot tone can be used to monitor optical filter's central frequency shift [14] (Fig. 5).

Fiber Nonlinearity Monitoring

Fiber nonlinear interference (NLI) is one of the major impairments. For uncompensated link, NLI can be treated as additive noise. The monitoring of nonlinear noise is not trivial. An artificial neural network model to estimate fibre nonlinear noise-to-signal ratio based on amplitude noise covariance of received symbols is presented[5,6]. 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[7,8]. NLI impacts the behaviour of the carrier phase recovery, hence from the recovered phase waveform, it is possible to learn and predict the NLI[9].

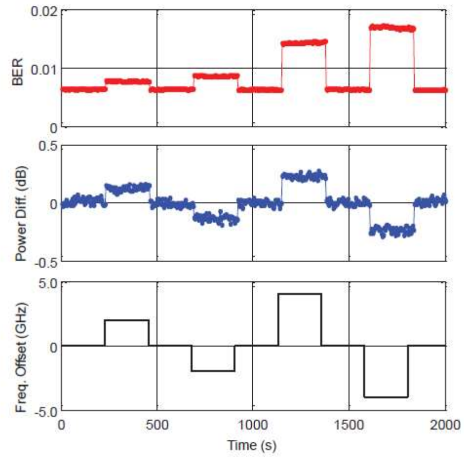

Fig. 5: Demonstration of real-time filter frequency offset induced impairment monitoring. Bottom: frequency detuning between signal and filter center; Middle: power difference between the signal positive and negative bands monitored by the dual-band pilot tone technique; Top: BER evolution.

To monitor the nonlinear noise directly, zero power gap is inserted into the signal, and AM-PT is applied. At the receiver, both the ASE noise and nonlinear noise are accumulated in the gap. However, only the nonlinear noise is modulated by the AM-PT (nonlinear noise power is proportional to local signal power), the ASE is generated in the amplifiers, therefore not modulated by the AM-PT (Fig. 6). The detection of nonlinear noise power in the receiver is then straightforward, requiring only a processing block in the Rx DSP, and is essentially free of hardware cost[15].

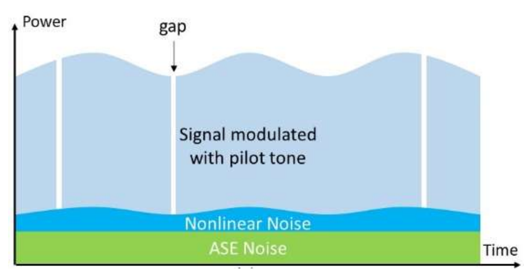

Fig. 6. Nonlinear noise monitoring principle: zero power gap and AM-PT is applied to signal, the nonlinear noise is the power in the gap with AM-PT.

This direct nonlinear noise monitoring approach provides excellent accuracy, and can be used for in-service monitoring[16]. Fig. 7 shows a comparison of the nonlinear noise induced OSNR penalty measured by standard BER~OSNR method and PT method, with an error of less than 0.2 dB.

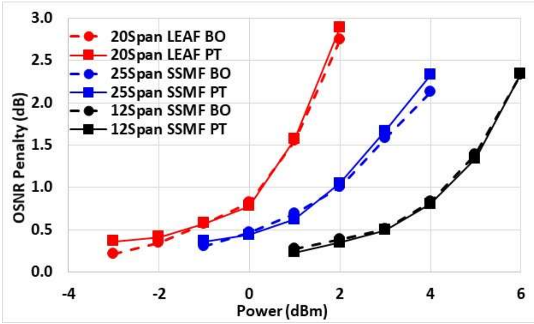

Fig. 7. Nonlinear noise induced OSNR penalty measured by standard BER~OSNR method and PT method.

Another advantage is speed, with millisecond monitoring capability, it is used to diagnose the transient behaviours during channel add/drop. In Fig. 8, the 10ms scale nonlinear noise monitoring capability is demonstrated with a real-time transceiver.

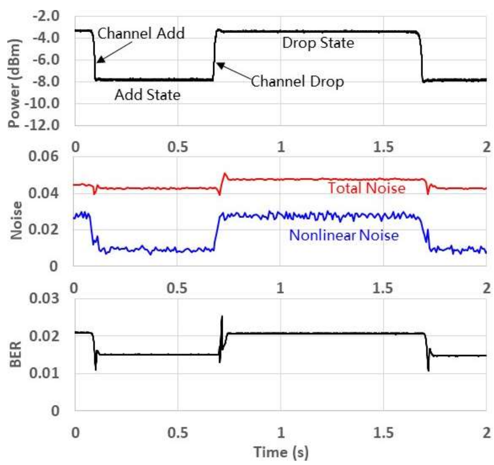

Fig. 8. Real-time performance monitoring during channel add/drop.

In an optical link, higher launch power into the fiber reduces the ASE noise and increases the nonlinear noise. As is well-known, the optimum launch power corresponds to the condition that the ASE noise power is twice of the nonlinear noise power, which is confirmed in Fig. 9.

Conclusion

Optical performance monitoring is important for optical network operation, and low cost is essential for a monitoring technology to be widely used. With powerful DSP capability in coherent transceiver, many OPM functionalities can be implemented at very low or no cost.

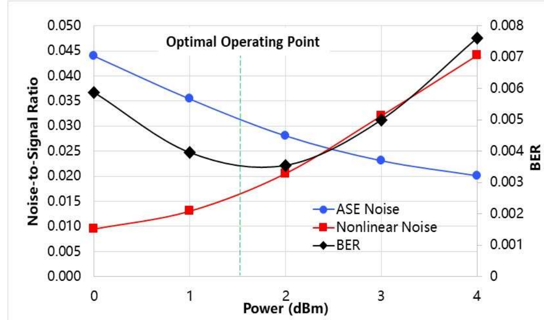

Fig. 9. Demonstration of optimal operating condition. ASE noise, nonlinear noise, and BER are simultaneously monitored as a function of launch power. Minimal BER occurs when the ASE noise is twice the nonlinear noise.

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