Optical Performance Monitoring and Network Diagnosis in Reconfigurable Optical Networks

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ABSTRACT

We review some of the recent developments of optical performance monitoring (OPM) in various aspects: (i) the enhancement of monitoring resolution, (ii) multi-impairment monitoring, and (iii) OPM network optimization. In particular, some of the studies on the optimization of performance monitoring networks to achieve the optimal monitoring locations and the number of monitoring probes are discussed.

Keywords: optical performance monitoring, optical signal to noise ratio, dispersion monitoring, polarization mode dispersion, network diagnosis, fault diagnosis, reconfigurable optical network

1. INTRODUCTION

Optical performance monitoring (OPM) covers a very wide range of measurements intended to help assure the network performance and is essential for service providers [1]. It is used for various applications including signal quality characterization, fault management, active compensation, and quality of service provision. The monitoring metrics include optical signal-to-noise ratio (OSNR), chromatic dispersion (CD), polarization-mode dispersion (PMD), fiber nonlinearities, and even path traces. All-optical reconfigurable mesh networks impose great challenges on OPM because of the signal transparency and non-static configuration for different channel [2]-[3]. Various groups have proposed ingenious schemes for OPM [4]. In this paper, we will review some of the recent developments of OPM in various areas. In Section 2, we review a few schemes proposed to further enhance the monitoring resolution and to make OPM more robust. Section 3 will discuss multi-impairment monitoring. In Section 4, we will consider the optimization of performance monitoring from the network point of view. The theoretical study on the optimization of monitoring location and monitoring information will be given. Section 5 concludes this paper.

2. ENHANCEMENT OF OPM'S MONITORING RESOLUTION

Many schemes have been proposed and employed to monitor different impairments in optical communication systems. One critical consideration is the monitoring resolution or sensitivity. In the following, we will present various resolution-enhanced schemes for OSNR and CD monitoring.

Polarization-assisted OSNR monitoring based on the measurement of degree of polarization (DOP) has attracted much attention, due to its simplicity and high efficiency [5]-[6]. However, the OSNR monitoring sensitivity is degraded in the high OSNR region, resulting in high estimation error and limited dynamic range. In order to enhance the monitoring sensitivity of polarization-assisted schemes, we experimentally investigate the DOP-based OSNR monitoring sensitivities using different optical filtering schemes [7], as shown in Fig. 1. Using symmetric or off-center optical filtering with different filtering bandwidth before the DOP measurement, it is possible to enhance the DOP sensitivity to input OSNR. As shown in Fig. 1, broad-band symmetric filtering will include more ASE noise for DOP measurement, whereas off-center narrow-band filtering will extract a smaller part of the signal's power. Both approaches result in de-polarization for the filtered signal, which will reduce the measured DOP value intentionally. Hence, this will allow the OSNR monitoring to be operated at a high sensitivity region of the DOP response curve. The results show that off-center narrow-band optical filtering dramatically enhances the OSNR monitoring sensitivity. In a 10-Gb/s RZ-OOK system with a 28-ps pulse-width, the symmetric broad-band and off-center narrow-band filtering techniques show a similar improved monitoring sensitivity, 0.63 %/dB in the high OSNR region. In a 40-Gb/s RZ-OOK system with a 2.5-ps FWHM pulse-width, a high monitoring sensitivity of 3.14 %/dB is successfully achieved in the high OSNR region by using 1-nm off-center narrow-band filtering with bandwidth of 0.22 nm. The proposed scheme is simple and easily upgradeable.

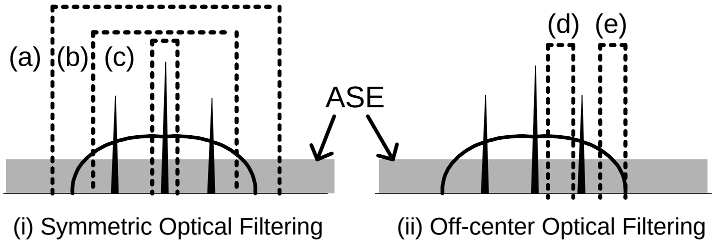

Fig. 1 Illustration of optical filtering scheme for DOP-based OSNR monitoring using symmetric or off-center optical filtering.

We have proposed a novel and simple in-band OSNR monitoring technique using phase modulator embedded fiber loop mirror (PM-FLM) [8]. This technique measures the in-band OSNR accurately by observing the output power of a fiber loop mirror filter, where the transmittance is adjusted by an embedded phase modulator driven by a low-frequency periodic signal as shown in Fig. 2. Various characterization experiments have shown that the proposed technique has high accuracy, high sensitivity and large dynamic range in OSNR measurements. For instance, the monitoring errors are less than 0.5 dB for OSNR between 0 to 40 dB in a 10-Gb/s NRZ system. This technique has also been shown to be PMD insensitive, CD insensitive, bit-rate independent, and robust to partially polarized ASE noise.

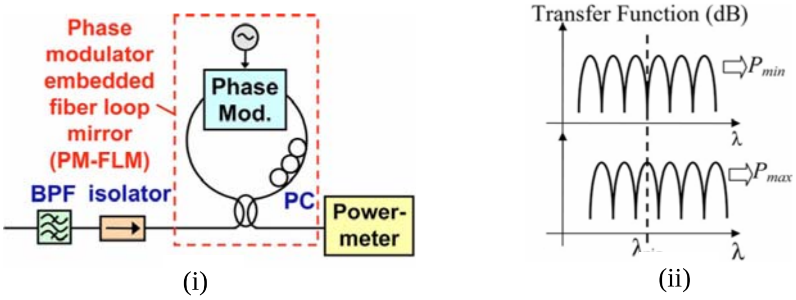

Fig. 2 (i) A schematic diagram of a proposed OSNR monitoring module using polarization modulator embedded fiber loop mirror (PM-FLM). PC, polarization controller; (ii) Illustrated PM-FLM transfer function when destructive and constructive interference for the data signal occurs.

For long-haul transmission, some advanced modulation formats such as differential phase-shift-keying (DPSK) are preferred. Therefore it would be interesting if the monitoring scheme can be generalized for different modulation formats. In [9], X. Liu et al. generalize a monitoring method using 1-bit optical delay interferometer (ODI) that has a tunable passband to allow the OSNR monitoring for both OOK and DPSK signals. The method was successfully applied to the monitoring for a 42.7-Gb/s DPSK signal using a partial-bit ODI.

Several techniques for monitoring chromatic dispersion and signal quality have been reported. One of the simplest techniques for chromatic dispersion monitoring is measuring the RF power of the signal clock tone, as it does not require any additional modulation on the data [10]. However, in these CD monitoring schemes based on RF power measurement, the dispersion resolution is relatively limited, especially in the low dispersion range. It is not suitable for the adaptive post-compensation system, where the dispersion is monitored after tunable dispersion compensator, and the measured residual dispersion varies in the low dispersion range. In [11], we experimentally demonstrated a resolution-enhanced residual chromatic dispersion monitoring scheme using half-bit delay-interferometer (HB-DI) filtering based on the RF clock-tone monitoring in a 28-ps 10-Gb/s return-to-zero on-off-keying (RZ-OOK) system as shown in Fig. 3. After using an HB-DI at the end of the transmission fiber, the amplitude of the RF clock-tone is related to a sine function, rather than a cosine function, of the accumulated dispersion. Therefore, the dispersion resolution can be improved significantly around zero dispersion region, thus it is suitable for the post-compensation.

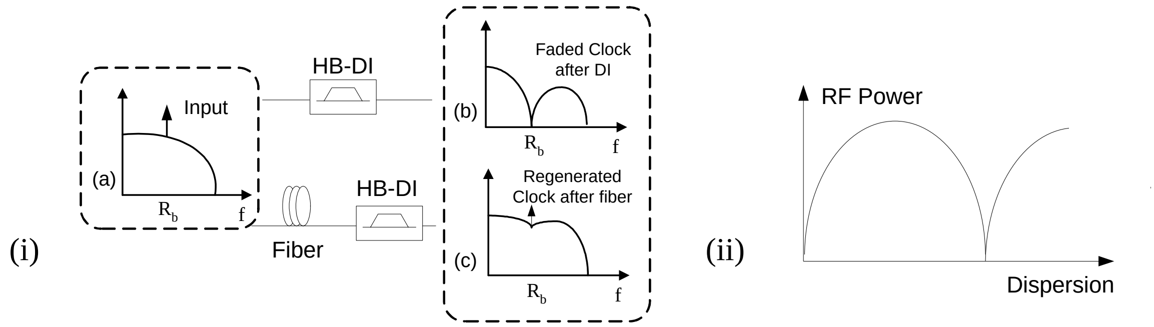

Fig. 3. (i) Operation principle of the proposed dispersion monitoring scheme. RF spectrum of (a) input signal, signal after HB-DI (b) without and (c) with dispersion; (ii) RF power of clock tone as function of dispersion in the proposed scheme.

We also proposed and demonstrated a novel technique for monitoring dispersion using a birefringent fiber loop (BFL) in a 10-Gb/s NRZ-OOK system [12]. By feeding a signal distorted by chromatic dispersion into a fiber loop which consists of a high-birefringence (Hi-Bi) fiber, the dispersion experienced by the signal can be deduced from the measured RF power at a specific selected frequency that is determined by the length of the Hi-Bi Fiber. This technique requires no modification at the transmitter, and provides large measurement range that is independent of data rate.

3. MULTI-IMPAIRMENT MONITORING

Many prior works in OPM have been focused on the techniques that monitor one type of impairment.

However, several impairments may coexist and affect the monitoring metric simultaneously. Most attempts are to devise a robust monitoring scheme to measure one type of impairment while reducing the effect from the other impairments. It is very desirable to develop monitoring techniques that use the same measurement module to quantify multiple signal degradations, or to distinguish impairment sources in the presence of various impairments, thereby achieving more cost-effective OPM. For instance, pilot tone has been use for the monitoring of CD, PMD, and OSNR by various means [2]. For the dispersion monitoring, it is based on measurement of the RF power fading created by the phase shift between the two side bands of the signal due to frequency dependent dispersion. For PMD monitoring, it is based on the fact that with PMD, the pilot tone power is degraded and can be expressed as a function of the differential group delay (DGD) in the transmission fiber. As for the OSNR monitoring, the amplitude of the pilot tone can be used to deduce the OSNR information. Since these three monitoring techniques all involve the use of pilot-tone, it is not very surprising that a monitoring module based on pilot tone measurement can be devised to monitor multiple impairments. In the following, we will present a few multi-impairment monitoring schemes some of the recent developments for multi-impairment monitoring.

In [13], Dods et al. proposed an asynchronous delay-tap sampling scheme to obtain an impairment diagram, called phase portrait. It contains information on the sources of impairments including OSNR, chromatic dispersion, PMD, filter dispersion or their combination. It has been demonstrated that signal quality, the OSNR, and multiple simultaneous impairments, including chromatic dispersion, PMD and filter offset, can be separated and quantified by a single monitor [14]. Further experimental results are presented in [15]. Y.K. Lize et al. demonstrated a simultaneous and independent monitoring of CD, PMD and OSNR using a ¼-bit delay Mach-Zehnder interferometer for NRZ-OOK, DPSK and Duobinary modulation formats [16]. In [17], C. Dorrer et al demonstrated the construction of signal constellation diagram to measure different kinds of impairments using linear optical sampling technique. They have experimentally demonstrated, using waveguide technology, the characterization of picosecond waveforms and high bit-rate eye diagrams, and the measurement of constellation diagrams at 10 and 40 Gb/s. It is highly desirable to simultaneously monitor PMD and OSNR using common monitoring module to achieve more cost-effective OPM solution. We propose and experimentally demonstrate a simultaneous PMD and OSNR monitoring by enhanced RF spectral dip analysis assisted with a local large-DGD element [18]. As shown in Fig. 4, by scrambling the polarization controller before the local large-DGD element, the position of RF spectral dip and the corresponding power will change. Therefore, the PMD and OSNR in the transmission link can be effectively estimated from the RF spectral dip shift and minimum RF dip power, respectively, as shown in Fig. 5. Experimental results show that this scheme can monitor PMD from 0 to 90 ps with less than 2-ps error and OSNR from 16 to 35 dB with less than 1-dB error in a 10-Gb/s RZ-OOK transmission system with a pulsewidth of 2.5 ps.

In addition to the saving by sharing the monitoring components for different impairment, further cost reduction can be attained if some components can be shared for multi-channel monitoring in WDM networks. One straightforward implementation is to monitor individual channel sequentially. This is at the expense of longer acquisition time for monitoring to scan through all channels. In [19], a multi-channel monitoring of chromatic dispersion and OSNR for 40-Gbit/s NRZ WDM system is demonstrated. The scheme is based on the RF-spectral analysis for simultaneous CD and OSNR monitoring. The scheme uses two shared electro-optical modulators for all WDM channels in the monitoring signals down-conversion process, thus reducing the number of high-speed electronic components required and the overall monitoring cost.

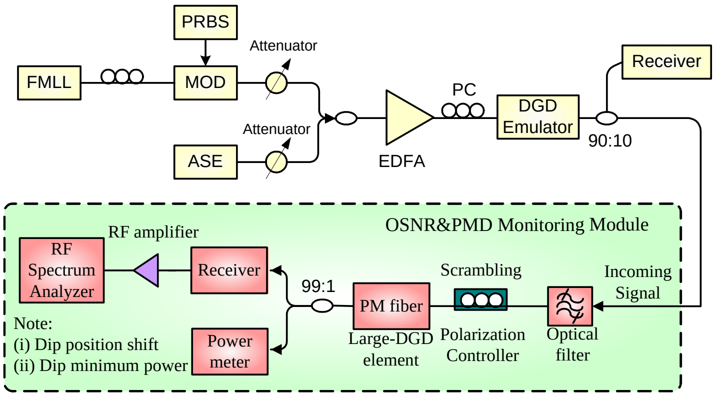

Fig. 4. Experimental setup for the PMD and OSNR simultaneous monitoring based on RF spectral dip monitoring

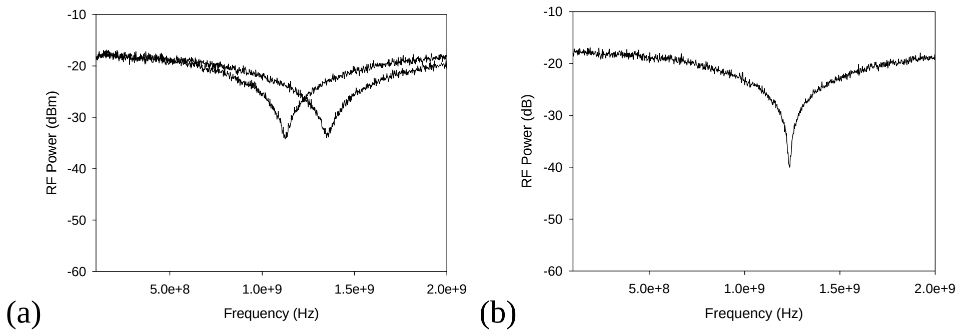

Fig. 5 (a) RF spectrum with the power dip shift with the large-DGD element of ~409ps and PMD emulator of 40ps, (b) RF spectrum with the minimum power measured at large-DGD element of ~409ps, PMD emulator of 20ps and OSNR of 35dB.

4. OPTIMIZATION OF PERFORMANCE MONITORING NETWORKS

From the carrier's point of view, "there is no level of performance monitoring that is superfluous; there are only levels that are too expensive" [1], to reduce the cost of monitoring systems, other than the reduction of the cost of monitoring device, it is desirable to optimize various parameters such as the number of probes, the amount of monitoring information, the locations of the monitoring units, etc. In an optical network, there exists correlation between the monitoring information at different nodes and links. We can consider that as the spatial correlation of monitoring signals. One of the examples is the fault diagnosis in a network. A single failure may trigger a series of alarms along its propagation path. So these alarms are highly correlated and a proper algorithm is needed to find the root cause of the alarms. In [22], Mas et al. classify a wide range of faults in transparent networks and introduce different categories of alarms that can identify different faults. For each fault in the transparent network, a set of alarms along the channel path are triggered. By considering the status of alarms as a binary vector, the paper proposed a systematic off-line approach to build a binary search tree so that, whenever a set of alarms are triggered, the algorithm of fault localization only deals with the traversing of the binary tree. Since multiple faults can trigger the same set of alarms, ambiguity may occur. In order to address the problem, Mas et al. extended the algorithm to find the best location for new monitoring equipment so that failures can be more precisely identified. The number of fault candidates can be minimize under two cases, one is to minimize the number of fault candidates according to a set of pre-defined channels or established channels, another one is to minimize the number according to the network topology, which means to minimize the number in the possible worst case.

Another way of fault diagnosis in a network is to actively inject a set of channels, called “probe”, to locate faults in the network. Wen et al. proposed a family of efficient fault-diagnosis algorithms to minimize the number of probe [19]. The authors consider link failures. Each link has two states, on or off, which means that the link is under normal operation or experience failure respectively. Whenever a failure occurred in a link, all channels, including the injected probes, that transverse it are dropped. Therefore, each probe gives a binary result, on or off. A result of “on” means all links along the probe are “on”, while result of “off” means at least one of the links experienced a failure. A Random variable is assigned to each link to represent the state. To monitor the whole network, which is equivalently find out the values of all random variables, probability of failure, the number of probe should be at least equal to the entropy of all random variables. Wen et al. consider the case of homogeneous links which means that all the state random variables are identical independent distributed (i.i.d.). The authors explicitly proposed a probing scheme such the number of required probes is asymptotically equals to the entropy limit. Moreover, it is derived that one probe per each link is optimal.

Rather than just retrieve the on or off status of each link, it will be beneficial to be able to estimate the accumulated impairments along a channel path before the channel is established. This provides some network management functions, such as channel setup, control and optimization. With the performance information, network operators can estimate the quality of different paths and regard it as a metric for path computation in the network layer. Ho et al [21] investigated the fundamental limit on the number monitoring units, based on the probing approach, to retrieve the linearly accumulated impairment induced in both nodes and link in an all-optical mesh network. It is shown that the minimum number of monitoring probe is equal to the node number and is independent of the number of link. These theoretical studies may provide some insights on the fundamental limits for optical performance monitoring. Ho et al. then consider an other model of monitoring [23] in which optical impairments are linearly accumulated in directional links and the impairments induced the two directions of the same link are independent. Two kinds of networks are studied. For networks that all nodes can initiate and terminate channels, the authors derived the fundamental limits on the number of monitoring units required to monitor the whole network. Monitoring schemes for different network topologies that achieve the limit of monitoring modules, together with their fault localization ability, are presented. In particular, it can be proved that only a single monitoring module is enough for any two-link-connected network. For networks with nodes that can only route channels, a set of bounds on number of monitoring units, and the corresponding monitoring schemes for different network topologies are derived.

5. CONCLUSION

In this paper, we have reviewed some of the recent results in OPM in various aspects, including higher sensitivity, wider dynamic range, generalized schemes for different modulation formats, generalized schemes for multi-impairment, and finally the optimization of monitoring networks.

Albeit it is uncertain how much monitoring is needed, OPM is clearly indispensable for future high capacity transparent mesh optical networks, as the stake is too high. Ingenious designs for performance monitoring, from the device level to the network level, are needed such that the monitoring information can be obtained more efficiently and effectively.

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