Optical and Higher Layer Performance Monitoring in Photonic Networks: Progress and Challenges

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***Abstract* — Optical performance monitoring (OPM) and optical network management (ONM) are essential in building a reliable and high quality of service system as the optical transmission system continues to evolve towards higher data rates, increased wavelength density and longer transmission distances. Traditional OPM primarily focused on achieving the desired functionality and prove to be insufficient for next generation networks. Thus necessity has arisen for sophisticated OPM to control complex network topologies and at the same time the cost of the OPM has to be fully justified on the basis of system's improved performance. In this paper, we first present a broad review of the OPM status and discuss their prospects and challenges ahead. Finally, the relationship of OPM to the higher layer and the role of ONM in maintaining the photonic networks are also reviewed.**

***Keywords* — Optical performance monitoring, fiber Bragg grating,, bit error rate, wavelength division multiplexing.**

1. Introduction

With the Internet becoming an increasingly important tool for both businesses and consumers, ensuring smooth operation of the massive global photonic network is a critical task. Every day billions of gigabytes of data flow through the complex web of optical cables and switches that span the globe. Dense wavelength division multiplexing (DWDM) has been deployed to meet this requirement by transmitting multi-carrier signals over a single fiber. It is not enough for service providers to deploy DWDM transmission system capable of delivering high-speed connections to their customers, because a short service disruption will affect a colossal amount of data. Service providers must provide reliable service for their clients and ensure that signals are arriving at their destinations undistorted. Furthermore, when problems arise, carriers must be able to locate faults and repair quickly and thus real-time optical monitoring of the various network elements is necessary for the stability and protection of the network. Without it service providers would be blind to problems in their networks.

From the very beginning, optical transmission systems have required performance monitoring. The transmission portion of the earliest systems was relatively simple and point-to-point links were deployed with electronic regenerators at regular intervals. Because the signals had to be regenerated electronically at each node and detailed performance monitoring was conducted fully in electronic domain. The development of Erbium doped fiber amplifier (EDFA) and DWDM have allowed the transmission system to carry huge traffic over longer distances, which makes the application of traditional performance monitoring methods in these systems become insufficient. For example, to monitor the operation of EDFA requires an additional, out-of-band optical service channel (OSC) that transmits the status of EDFA to the system's terminals. This type of monitoring optical devices is known as optical performance monitoring (OPM). It covers a very wide range of measurements, such as optical signal-to-noise ratio (OSNR), chromatic dispersion (CD), polarization mode dispersion (PMD), fiber nonlinearities etc., intended to help assure the network performance [1]-[2]. Thus, OPM is used for monitor the health of optical signal at physical layer and can provide information for fault management which consists of identification, localization, diagnosis, resolution and tracking of faults in a network. The other issue closely related to OPM is its communication with higher control layers for optical network management (ONM), which is responsible for network topology discovery, resource management, connection provisioning, fault management and performance management [3].

Today's all-optical reconfigurable mesh networks impose great challenges on OPM as well as ONM because of the signal transparency and non-static configuration for different channels [4]. Various research groups around the world have proposed ingenious schemes for OPM and ONM [5]. In this paper, we review the progress and challenges of OPM, its techniques, requirements, drivers and finally shed some light on higher layer performance monitoring that enables the management of network configuration, faults, accounting and security.

2. Impairments of optical networks

An optical impairment is a condition introduced by optical fibers or optical components that cause information loss in a signal. Optical impairments include laser noise, optical amplifier noise, receiver noise, CD, PMD and nonlinear effects. All optical impairments can be categorized into three types: (i) noise, which is the random signal fluctuations and signal level dependent and usually treated as a Gaussian process, (ii) distortion, which is the modification of the average signal waveform and it may be signal level or pattern dependent and can lead to bursty errors and BER floors, (iii) timing, which is the fluctuation in the time registration of bits.

Within these categories, there are many root causes, with many degrading effects that manifest in more than one type. The root causes cannot be specified in advance because they include all of the various modes of component failures. Thus, it is helpful to further divide impairments into either component fault effects or optical transmission impairments.

A. component faults

Passive and dynamic components will experience environments depending upon application, ranging from unprotected locations in harsh climates to benign indoor controlled temperature, humidity situations as well as aging. Due to these effects, component faults occur that include individual or multiple component malfunctions, improperly installed or configured equipment and damage or intrusion to the network that ultimately result component faults. The active components are usually telecom grade and they have fairly long-mean-time-between-failures of several years. The fault may occur in fiber, transmitter, receiver, optical amplifier, wavelength router and wavelength converter and so on. For example, transmitter fault occurs when a tunable or fixed tuned laser, its monitor photodiode, or its driver circuitry used at the transmitter fails. This can be sensed by the photodiode that is packaged along with the laser or the laser driver senses the bias current of the laser diode and triggers a threshold crossing alert if it is not within normal limit. The use of fiber Bragg grating (FBG), pilot tones and spectral analysis are simple and attractive to monitor components faults [2], [7].

B. Transmission impairments

As the optical industry moving to higher data rates, it raises significant network deployment and operational issues for carriers and service providers. At increased transmission speed and fiber distance, fiber impairments, such as CD, amplifier noise, optical filter distortion PMD, etc., put barriers to the cost-effective system deployment and ongoing operation. In practice, all of these effects are controlled through the network design. Engineering rules and transmission margins are established to address the worst-case impact of specific impairment on a particular system. In order to achieve long link length, optical impairments, such as EDFA noise, CD and PMD are carefully controlled. Interchannel interactions accumulate noise as a function of distance and the number of channels. Prediction, monitoring and control of nonlinear impairments are complicated by interactions among impairments.

3. Drivers of Optical Performance Monitoring

OPMs are essential elements in the realization of all-optical networks. Monitors support fault isolation and detection and taking actions before transmission errors occur that would ensure a higher quality of service (QoS) for the network. Traditional ring-based networks cannot effectively manage the high growth and dynamic nature of the bandwidth demands. Due to the emergence of photonic switching, service providers begin to deploy the photonic mesh network, which will provide more efficient utilization of the DWDM network resources. While clear advantage have been identified for increased transparency and bit rates in this type of network, these trends also offer some unique challenges in terms of technical rules and transmission margins. OPM might have a key role in assuring redundant protected bandwidth availability, dynamic traffic rerouting, tracking of the optical signals, number of channels in use and physical layer fault management [6].

Therefore, the main drivers towards new OPM schemes in the next generation optical network are as follows:

(i) Increasing deployment of all-optical networks *i.e.,* higher capacity, efficiency, stability, reconfigurability, flexibility, and security optical performance monitoring for enabling self-management of the physical layer;

(ii) New network architecture and supports dynamic reconfigurability to accommodate a convergence of different types of data traffic over the same network and monitoring without prior knowledge of the signal origin and transport history;

(iii) Network will be fully transparent, such that optical-electrical-optical (OEO) conversion will be eliminated and bit rate-, format- and protocol independent physical layer monitoring is needed; and

(iv) Stringent customer requirements for guaranteed QoS.

As the evolution of optical communication network and its traffic growing faster, the main challenge for network providers is to reduce the cost of managed bit per km while maintaining the QoS in a satisfactory level. Now we will evaluate a couple performance monitoring techniques

4. Performance Monitoring Techniques

In this section, an overview of the available optical performance monitoring techniques is given. Although monitoring may reduce the risk of a failure to a minimum, it cannot be considered as a compensating mechanism for system deficiencies. In high-speed DWDM networks (> 40 Gbit/s), signal characterization parameters such as OSNR, CD, PMD or nonlinear distortion require close observation [7]. There have been several attempts to identify a standard set of OPM parameters. Since, OPM is physical layer monitoring and therefore the required OPM depends strongly on the physical network design. Different OPM parameters need different monitors and certain parameter may require costly technology. List 1 shows a list of many possible measurements that can be made on optical signal [11].

List 1. Physical layer measurement for OPM:

i) average power (per wavelength of aggregate)
ii) peak power
iii) pulse/bit shape

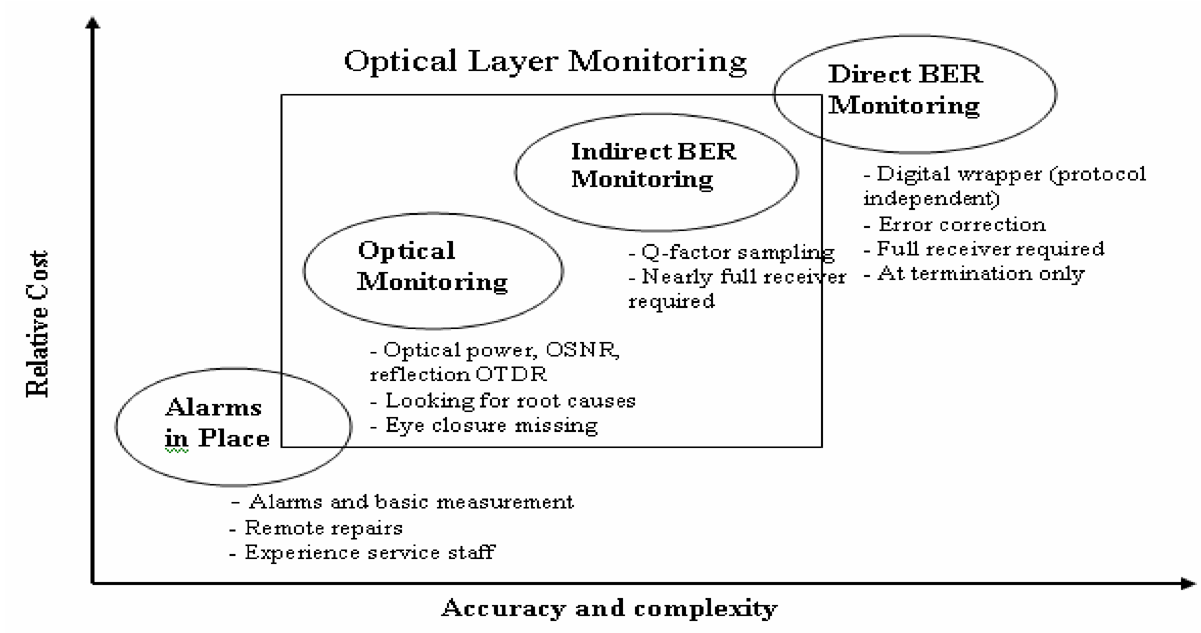

Fig. 1: Performance monitoring option [8]

iv) eye diagram
v) intensity/field autocorrelation
vi) amplitude power spectrum (RF spectrum)
vii) polarization state
viii) optical spectrum (wavelength)
ix) amplitude histogram (syn. and asynchronous)
x) Q-factor/ bit error rate
xi) PMD (DGD including higher order) and CD
xii) phase/optical carrier characteristics

Fig.1 shows different OPM options that include cost, technique, accuracy and their complexity. Since the early days of WDM, we witnessed many significant changes. The number of channels has increased, channel spacing has decreased, the bit rate increased and as a whole, the number of analog parameter measurement has changed. Depending on the number of parameters monitored simultaneously, the OPM can be classified as [5] (i) single parameter physical layer monitoring and (ii) multiple parameter physical layer monitoring. Again, depending on the type of application domain (such as transparent circuit switched or dynamically reconfigurable network) OPMs are also categorized as current and advanced.

A. Single parameter physical-layer monitoring

The single parameter OPM includes a number of parameters that can be monitored alone in the system. This type of measurement is categorized into three types: (i) signal loss monitoring, such as inline component failure, fiber cuts etc. (ii) signal alignment monitoring, such as alignment of the signal wavelength, filter position etc. and (iii) signal quality monitoring, such as PMD, CD, BER, OSNR, Q-factor etc.

It is necessary to monitor the fiber and EDFA status constantly for fault management due to fiber cut or EDFA failure to avoid the colossal data loss or system outage. It is also critical to monitor optical cross-connects (OXC) and optical add-drop multiplexers (OADM) for wavelength routing failure due to switch failure or wavelength mismatch due to environmental changes. Usually FBG for fiber failure and pilot tone or spectral analysis is employed for inline component monitoring [9]-[10]. In the DWDM dynamic reconfigurable networks require accurate in-band OSNR measurement for link provisioning, signal quality characterization, fault localization and intelligent routing. The in-band OSNR measurement can be done by polarization assisted approach [11]. PMD is also a big obstacle in many fiber optic transmission systems and as the bit rates increases 10 Gbit/s or beyond, its impact will be even greater. Common PMD monitoring approaches include using degree of polarization and the RF notch frequency components [12].

B. Multiple parameter physical-layer monitoring

We found that many works in OPM have been focused on techniques, which monitors only one type of impairment. However, several impairments may co-exist and affect the monitoring metric simultaneously. Most attempts are made to devise a robust monitoring scheme for measuring a single impairment while reducing the effect from the other impairments. It is very desirable to quantify multiple signal degradations or to distinguish impairment sources in the presence of different impairments and thus achieving more cost effective OPM. For instance, pilot tones have been use for the monitoring of CD, PMD and OSNR by various means [4]. It has been demonstrated that signal quality, the OSNR and multiple simultaneous impairments including CD, PMD and filter offset can be separated and quantified by a single monitor [13]. Y. K. Lize *et al.* [14], demonstrated a simultaneous and independent monitoring of CD, PMD and OSNR using 1/4–bit delay Mach-Zehnder interferometer for NRZ-OOK, DPSK and duobinary modulation formats.

It is seen that the research trend is to use a simple scheme to characterize multiple parameters concurrently is a cost effective manner. It is however, a great research challenge to decouple one type of impairment from o a host of others, especially when the number of impairments goes up and the difficulty scales accordingly.

C. Current and advanced OPM techniques

Dynamically reconfigurable transparent optical networks will require advanced OPM techniques to allow for real time control of compensation devices and facilitate network management operations, including reporting degradations for alarm correlation and fault localization. Currently available OPM techniques are optical spectrum analysis (OSA) using FBG or tunable filters as diffraction devices [15] and polarization nulling [16]. OSA monitoring is based on analyzing the optical spectrum of the detected signal. Depending on the measurement resolution, scanning can take from about 100 ms to few tens of seconds to complete a measurement across the entire C-band. The main limitation of the OSA based noise measurements is that these assume the power levels on both sides of the channel equal to the in-channel noise level. This assumption becomes invalid for current DWDM networks due to signal overlap from neighboring channels, in-line filters, spectrum broadening from nonlinear effects and four wave mixing induced noise. The polarization-nulling method overcomes some of the OSA limitations present in OSNR measurements. In this method, it is assumed that an optical signal is completely polarized whereas noise contributions are completely no-polarized. The optical noise can be detected by measuring the degree of polarization. But the long measurement acquisition time (>20 ms) of these OPM devices make them unsuitable for performance monitoring in dynamically reconfigurable L. Meflah *et al.* [4], describes a number of currently available and advanced optical OPM techniques and assesses their suitability for use in dynamically reconfigurable transparent optical networks. Advanced OPM techniques are sensitive to the OSNR. In general, these techniques can either be analog or digital. Digital methods have strong correlation with the BER, but are usually less effective at isolating the effects of individual impairments. Advanced techniques include RF spectrum analysis [2], histogram sampling methods [7] and electrical equalizer coefficient comparison [17]. These advanced OPM techniques allow for measurement of the degradation effects without knowing the path history of data. The main advantages and limitations of current and advanced monitoring techniques for using dynamically reconfigurable networks are depicted in Table 1.

5. Higher layer performance monitoring

ONM is essential to ensure efficient, reliable and continuous operation of any photonic network. Network management function includes the management of configuration, faults, performance, accounting and security, all of which are usually related to one another [18]. The broad area of OPM includes an extremely wide range of functionality intended to be included in a communication network to improve the network's performance. In principle, the data generated by OPM is communicated to its higher layer for ONM. Fig. 2 depicts the relationship between OPM and ONM module in a long haul network. Monitoring at the node level is to ensure signal presence at the input and output as well as to provide sensitivity to both noise and distortion effects. Sometimes, different activities like PMD monitoring for tuning a PMD compensator and power monitoring for dynamic gain equalization (DEG) uses some OPM functions, where the OPM metric may remains locally at the network node level for controlling the network element directly. For other functions, like fault monitoring and network element status monitoring, the OPM metric have to be disseminated to the higher-layer element management system (EMS) or ONM to engineer optical paths and initiate administrative actions.

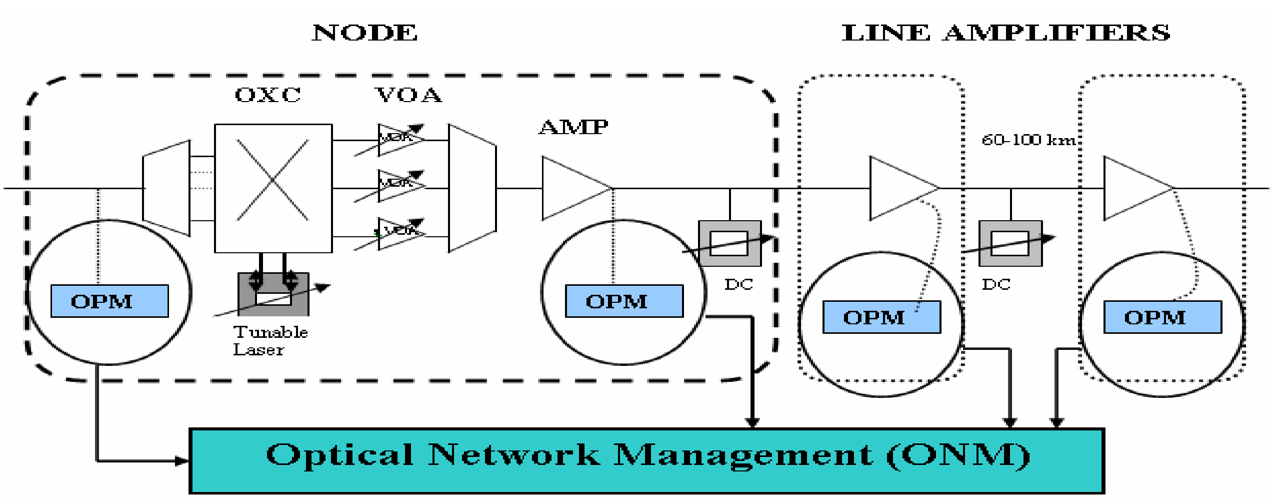

Fig.2: Relationship of OPM and ONM in a long-haul photonic network

Interaction between OPM and higher layer EMS or ONM become a critical issue. Questions arise such as what information should be passed around the network in order to keep ONM scalable. There are several research initiatives to enable the most effective interaction between OPM and ONM. In practice most of the network management functions in current OPM schemes are performed locally by agent [19]. The agent is then communicates with a network management center using simple network management protocol (SNMP). This protocol enables the management platforms to query management information of heterogeneous multi-vendor devices in a uniform way. The network functions can be controlled centrally or in a distributed manner. Only one controller is active to perform the network management functions in a centralized network. On the other hand, multiple controllers share the network management functions in a distributed network management system. Usually, a distributed ONM is more robust but is also more complicated in terms of maintaining the consistency of the network inventory database and distributed restoration of part or the entire network. A typical management platform of ONM is shown in Fig. 3

6. Challenges of OPM and ONM

Early deployments of WDM technology did not present a strong need for optical layer monitoring except during system turn-up to ensure balance of power throughout the network. In the last few years the advances in WDM is tremendous in terms of bit rate and number of channel supported by the system. For flawless system operation and maintenance of these networks accurate measurements of some key optical parameters are critical for guaranteed service level agreements. As a result, OPM and ONM face technological, technical and business challenges.

There have been increasing interests in the deployment of reconfigurable optical add/drop multiplexers (ROADM) and multi-degree optical switches recently. This trend will certainly accelerate the evolution toward dynamically reconfigurable optical networks, where the optical channels are added/dropped or cross-connected directly in the optical layer using WDM technologies. However, as the network becomes more and more transparent, it will be more difficult to monitor the qualities of optical signals by the OPMs and locate the sources of faults

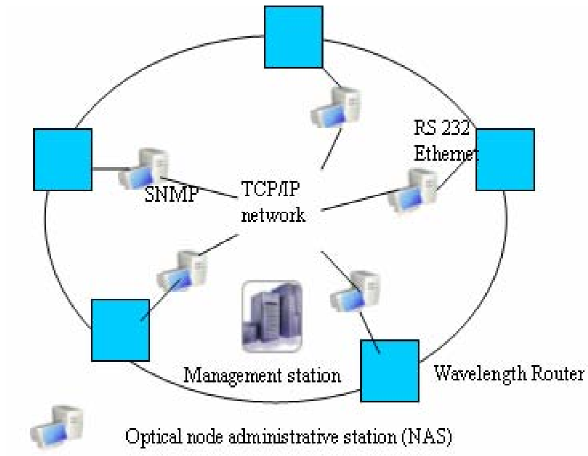

Fig.3: An ONM platform for a typical optical network [19]

In an optical network, there exists correlation between the monitoring information at different nodes and link. It is great technological challenge to optimize various parameters such as number of probes, amount of monitoring information, the location of monitoring units etc. to reduce the cost of monitoring systems rather than the reduction of the cost of OPM devices. Impairments such as distortion due to CD or PMD, nonlinearities or other phenomena may differ from channel to channel than in point-to-point systems. Many research groups are actively engaged in developing new techniques to meet these demands. An example of one promising technique for monitoring signal quality is the Quasi-bit error rate (Q-BER) [7]. The prospects for these developments are significant. Network operators are looking for ways to find best monitoring and management techniques of their networks and only advanced technology can assist them towards that goal.

One of the biggest challenges for ONM developers/vendors is the demand by service providers to improve network management capabilities with moderate cost. ONM designers/developers have to carefully analyze issues such as performance management, fault management, configuration management and restoration management

Table 1: Comparison between current and advanced OPM techniques [4]

Parameters	**Current OPM techniques**	**Advanced OPM techniques**			
		RF pilot tones	**RF clock tones**	**Sampling**	**Electrical equalizer**
Monitor	- OSNR - Channel power - λ accuracy	- CD - PMD - OSNR	- CD - PMD - OSNR	- CD - PMD - OSNR	- CD - PMD
Main advantage	-Currently available	- Fast response time (sub ms)	- Fast response time (sub ms)	-BER estimation	-Potentially cheap
Main limitation	-Response time slow (> 20 ms)	-Require transmitter modification	-Potentially expensive (single channel operation)	-Response time very slow(>1s)	- Limited to 10 Gbit/s systems -Require transmitter modification

7. Conclusion

For the efficient operation of modern DWDM network, it is essential to monitor the key parameters directly in the optical layer. OPM is one of the key enablers in terms of providing a high QoS and flexible services to the clients. Maintaining QoS while operating the photonic network at higher data rates and capacities is the driving force behind an increasing demand for optical layer monitoring. A comprehensive list of OPM techniques ranging from components fault to signal quality monitoring is presented. The current and advanced OPM for reconfigurable photonic networks as well as simultaneous monitoring techniques are discussed in detail. Although the future of photonic network is difficult to predict, the value of OPM increases with increasing transparency. We have also focused the role and functions of ONM that monitors the network management functions continuously, alerting operators and managers in real-time by manipulation different network parameters and ultimately provides improved network availability at satisfactory QoS level.

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